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BUREAU OF PUBLIC ROADS

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IMPROPER DESIGN PERMITS SURFACE WATER TO SATURATE AND SOFTEN SUBGRADE SOIL UNDER EDGE OF PAVEMENT

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THE PRESENT STATUS OF SUBGRADE STUDIES

Reported by A. C. ROSE, Associate Highway Engineer, U. S. Bureau of Public Roads

The review of the progress of subgrade research to which this entire issue is devoted is the first of a series of similar articles which will present an abstract of the results of highway research in all its phases. Other articles dealing with the status of research affecting the design and construction of road surfaces, the economics of highway transportation, highway finance and administration, and other aspects of the highway situation will appear in later issues.

Glenn Frank, the editor of the Century Magazine, who retires this month to assume the presidency of the University of Wisconsin, writing in his valedictory editorial of the need of utilizing the contributions of research in all the sciences as the basis for a renaissance of western civilization, has so fully expressed our idea in presenting these reviews that we can no better explain our purpose than by quoting a single paragraph.

"The end of all research and analysis," says Mr. Frank, "is synthesis and social application. This must mean, it seems to me, that every now and then we must gather up the results of a period of research into what, for want of a better term, may be called a series of tentative dogmatisms upon which society can act until further research reveals wiser bases of action."

Mr. Frank is referring, of course, to a broad application of the product of all the sciences to the condition of society in general, but if he had been writing directly to highway engineers he could not have touched more accurately upon the present need.

A brief exposition of the existing knowledge of highway subgrades should be of value at this time in order to bring together in one paper the principal findings. From these the trend of the investigations may be indicated, the missing data may be identified, and the specific studies may be determined which are necessary in order to make the next step in the progressive development of this subject. In general, this article will discuss the results of experience and research which add to the possibility of distinguishing between good and bad subgrade soils. By quotations from test data gathered from many sources it will present the concrete findings which may now be practically applied to determine the design of a pavement on a specific kind of subgrade; and, by revealing the missing links in the chain of information, it will indicate the further research immediately required to accelerate the progress of our knowledge concerning this fundamental phase of highway design and construction.

It is gratifying to note the rapid advance toward the solution of the subgrade problem which has occurred during the past decade. Prior to this period one might have searched through all the engineering literature and found nothing more than general and indefinite observations on the subject. This discussion will contrast these general observations with the more scientific treatment to which the problem has recently been subjected, prominent in which have been the laboratory and field tests of the Bureau of Public Roads, the Pittsburg test road in California, and the Bates test road in Illinois, together with the contemporaneous studies of the various State highway departments.

Reference will be made principally to the specific data which are believed to be of practical use in highway design. Theoretical studies which up to this time do not seem to have developed any principles of practical value will be avoided.

An illustration of this is the difference of opinion which seems to exist concerning the character and effect of the colloidal fraction of a soil. One of the latest concepts of this matter seems to have been given by P. L. Gile, of the United States Bureau of Soils.[1] The following quotations from this article are believed pertinent:

"It is now recognized that the colloidal material is not of definite composition and that it may form a large part of the whole soil. * * *

"The quantity of colloidal material in the soil probably varies from a trace to almost 100 per cent. Usually, loams contain from 20 to 25 per cent of colloid; coarser textured soils contain less; and clays usually contain from 40 to 50 per cent, although they may run much higher. A few soils that have been examined appear to be more than 90 per cent colloidal material. These figures are not based only on determinations by ratio methods. From a sample of Houston clay soil 65 per cent of colloidal material was actually isolated. By far the greater part of the isolated material was made up of submicroscopic particles. * * *

"The quantity of colloidal material in a soil does not appear to differ greatly, as a rule, from the quantity of the old 'clay fraction' given by various systems of mechanical analysis. It is now evident, however, that, in certain cases, the nature of the clay fraction (which is largely colloidal material) may be a more important factor in determining how a soil will act than the quantity of this separate. * * *."

PRINCIPAL FINDINGS OF SUBGRADE STUDIES TO DATE

THE QUANTITY AND CHARACTER of the clay content of a soil in the United States seems in general to determine whether it will make a good or bad subgrade.

Laboratory and field tests have been devised for distinguishing between good and bad subgrade soils.

The moisture equivalent percentage seems to be a critical value in respect to the bearing power of a subgrade soil. When wetted beyond this percentage, the bearing power seems to fall off rapidly.

At a depth below the surface of the soil sufficient to be removed from the influence of surface water and other forms of free water, there are indications that the moisture content rarely exceeds the moisture equivalent percentage.

There are indications that by proper subgrade design it may be possible to control the moisture content of a subgrade soil to a maximum value approximately equal to the moisture equivalent percentage.

Construction methods which may be used to overcome the effect of bad subgrade soils are as follows:

(*a*) Use coarse-grained soils for building fills over heavy clay soils.
(*b*) Use side ditches of special design.
(*c*) Use tile drains beside but not under the pavement.
(*d*) Use a granular subbase.
(*e*) Thicken the pavement.
(*f*) Add steel reinforcement.

[1] Recent investigations of soil colloids, by Philip L. Gile. Proceedings of the American Society of Civil Engineers, vol. 51, No. 5, May 1925.

It is evident from these quotations that the free colloidal material which may be isolated from a soil sample by the process of centrifuging may represent only a portion of the entire colloidal material present or else all of it. The balance of the colloidal material seems to be in a combined form and exists in particles larger than those which may be identified by centrifuging.

The above data, therefore, confirms the conclusions arrived at by the Bureau of Public Roads that the portion of the suspension clay in a soil which may be isolated by centrifuging is usually such a small fraction of the entire soil sample that its effect upon the various physical properties of the soil is of minor importance as compared with the effect of the entire clay fraction. An examination of the laboratory determinations of the bureau shows that the variation of the volumetric shrinkage values and other characteristics of 57 samples of different soils do not vary with a corresponding variation in the suspension clay (which resembles the colloidal material) but rather with the variation of the entire clay fraction including the suspension clay. [2]

After giving examples which indicate the trend of engineering opinion, an attempt will be made to harmonize the data and by synthetic process to bring out general conclusions which are representative of the most advanced practice. These will include construction methods used on bad subgrade soils. It will be evident that our present knowledge is far from satisfactory either as to degree or extent. The paper will conclude, therefore, with brief allusions to the studies which are believed of critical importance at this time in order to hasten the solution of the problem.

QUANTITY AND CHARACTER OF THE CLAY CONTENT SEEM TO DETERMINE SUITABILITY OF SUBGRADE SOIL

All the data submitted in this discussion point to the conclusion that, in the United States at least, the amount and character of clay in a soil determine its suitability for a highway subgrade. The results enumerated here should not be applied in foreign countries without a careful check against the local conditions. As Mr. H. H. Bennett [3] points out:

"In humid tropic countries there are very extensive areas of clay of exceedingly fine texture, which are markedly unlike the common clays of the temperate zone in their physical characteristics—notably in their open nature. The colloidal material has reached an advanced stage of weathering which gives the property of flocculency or a tendency to segregate into clusters, and the colloids do not mix with water readily. This gives rise to a condition of porosity which permits ready downward passage of rainwater. In parts of Central America there are clays of this nature that will plow into a good condition of tilth immediately after a rain or even while rain is falling. Types of this kind possess but slight plasticity and stickiness, and will serve admirably as subbase material even where almost the entire mass is made up of particles as fine as the finest clay. In Cuba large areas of very fine-textured red land are so porous that practically all of the rain passes downward, the run-off being insufficient to develop streams or drainage depressions. In the humid tropics as in the humid temperate zone, the pale yellow, bluish and mottled clays will be found least satisfactory for subbase material.

"In determining the clay content of soils with an exceptionally high percentage of organic matter, some deduction should be made for the organic matter, since this material, if thoroughly decomposed will be largely colloidal and will appear in the results as clay. In most clays this feature may be disregarded as the humus will probably be in that form which will not materially lessen the plasticity."

Generally speaking, however, all the data submitted in this country indicate—the character of the clay remaining constant—that good subgrade soils have a low clay content by mechanical analysis and bad subgrade soils are characterized by a high percentage of clay.[4] Some exceptions to this general statement have been pointed out by Mr. H. H. Bennett.

"Certain materials occurring in both the humid and arid regions, but much more commonly in the latter, will show in the mechanical analysis a composition as fine grained as the heaviest clay, and yet have very different physical characteristics from normal clays. These materials have a common property of being chalky. They are composed largely of carbonate of lime, or sulphate of lime, or both, and are known by such names as 'caliche,' 'plains marl,' 'gyp beds,' and 'rotten limestone.' All of them are low in content of colloids, at least in that type of colloids which impart plasticity and water-logging properties common to plastic clays.

"In the presence of excessive moisture the tendency of these materials is to remain firm rather than to become soft and miry. For this reason they can be relied upon generally as constituting good subbase soil for roads. The 'rotten limestone' formation is of very extensive occurrence in the Black Waxy Belt of Texas and southeastern Oklahoma, and the prairie region of Alabama and Mississippi; while the other materials underlie or outcrop over vast stretches of the Great Plains and arid regions.

"Clays of whitish, bluish gray, and pale yellow colors, or those showing a mottling or streaking of these colors, along with red, usually will be found more unfavorable (more subject to water-logging and lacking in firmness) than clays of red, brown, and uniform deep-yellow color. The common red clay of the eastern Piedmont region, for example, should make a good subbase for highways because it is of a more open nature and allows excess water to pass through."

Further studies may bring out the adverse qualities of the clay soils which will predetermine their usefulness for subgrades. At the present time, however, it seems that an increase in the quantity of the clay fraction, its character remaining constant, will increase the amount of heaving when the soil is frozen, increase the volume change of the soil due to shrinkage and swelling with variations in the moisture content, make the soil less permeable to water and thus make tile drains ineffectual in most cases in heavy clays, lend an elastic property to the soil when subjected to reversals of load, make it liable to permanent deformation when subjected to repeated or excessive loads when moist, increase the moisture-holding capacity of the soil, make the soil plastic when wet, increase the amount but decrease the rate of capillary movement of water, and reduce the allowable maximum bearing value of the soil.

[2] Physical properties of subgrade materials; by J. R. Boyd, Table 1. Proceedings of the American Society for Testing Materials, vol. 22, 1922, pt. 2, p. 350.
[3] Soil Scientist, United States Bureau of Soils.

[4] Researches on the structural design of highways by the United States Bureau of Public Roads, by A. T. Goldbeck. Transactions of the American Society of Civil Engineers, vol. 88, p. 264, 1925.

DISCUSSION INCLUDES OUTSTANDING OBSERVATIONS OF LAST DECADE

Some of the extraordinary observations concerning the behavior of subgrade soils which have been made by various investigators during the past decade are enumerated in this paper with the hope that they will be useful in solving the problems of some particular locality. These observations are given in detail at random without any attempt to correlate the individual cases because of the wide differences in degree and kind. They will bring out, for example, the moisture-resisting quality of the dry, brown silt loam of the Bates Road tests; the effects of admixtures such as granular material, Portland cement, and hydrated lime; the merits of a sand cushion under macadam roads; the use of tar paper on the loess soil of western Iowa to prevent hair cracking in concrete pavements during the curing period; the great volume changes occurring in adobe-soil subgrades; the value of layers or subbases of sand, gravel, or other granular material; the worst pavement failures prevalent in clay cuts of excavations; the impracticability of the selection and substitution of subgrade materials as a general solution of the subgrade problem; the adequacy of topsoil and sand-clay methods where local conditions permit but the restricted use of this process as a general solution of the subgrade problem;[5] and the enumeration of the laboratory and field tests which are now in use.

LABORATORY AND FIELD TESTS NOW IN USE

A number of laboratory tests have been devised by the Bureau of Public Roads.[6] These include the method of preparation of the soil samples; the determination by a mechanical analysis of the various percentages of sand, silt, and clay in the soil; the moisture equivalent test for the amount of water the sample will hold against 1,000 times the force of gravity; the capillary moisture test for the amount of capillary water the sample will take up under prescribed conditions; the volumetric shrinkage test for the amount the soil will shrink when oven-dried after being wetted to capillary moisture saturation; the comparative bearing value test to determine the relative bearing power of different soils with desired amounts of water; the slaking value of the soil or the quality of deliquescing in the presence of water; the dye adsorption test which is a measure of those properties of the soil that make for lack of stability. The interpretation of the tests for any given sample must be very general unless all the conditions existing in the field are known. In general, however, it may be said that soils with a high percentage of clay show a high moisture equivalent percentage, a high capillary moisture capacity, a high volumetric shrinkage percentage, a low comparative bearing value, a long time for the slaking value, and a high dye adsorption percentage.

Field methods [7] for identifying good and bad subgrade soils consist in the use of United States Bureau of Soils survey bulletins to determine the general characteristics of the soil, checked by establishing the lineal shrinkage percentage and moisture equivalent by methods outlined by the Bureau of Public Roads.

SUBGRADE SOIL STUDIES SEEN AS URGENTLY NEEDED

A CLASSIFICATION OF SOILS to conform as nearly as possible to the nomenclature and grading used by the United States Bureau of Soils in its soil survey bulletins.

The adoption of standard methods for making laboratory and field tests on subgrade soils.

The determination of the distribution of the maximum pressure through pavements and subbases of various types and thicknesses to subgrades of various soil types.

The determination of the maximum intensity of pressures permissible on soils of various types such as sand, silt, and clay. These maximum pressures for the same soil may differ in proportion to the area in contact with the subgrade resulting from the character and possibly the thickness of the pavement.

The determination of the maximum and minimum moisture contents which may be controlled in the subgrade soil by proper subgrade design in the various climatic regions of the country.

The determination of the test limits for good and bad subgrade soils for the various regions of the country, where climatic, soil, and traffic conditions are similar.

The determination of the test limits of soils, with varying degrees of permeability, which establish whether tile drains are unnecessary, effectual, or worthless.

The discovery of the stages which accompany the phenomena of freezing of soils under existing pavements.

THE OUTSTANDING FINDINGS OF PAST AND PRESENT SUBGRADE STUDIES

Early subgrade investigations.—Intensive studies of the character of the subgrade to determine the relative stability of various soil types for foundations for road surfaces have been initiated only within the last five years. But even at this late date it is still a common occurrence to see the safe load to which foundation material may be subjected expressed somewhat as follows:

Safe load per square foot

	Tons
Ledge rock	36
Hardpan	8
Gravel	5
Clean sand	4
Dry clay	3
Wet clay	2
Loam	1

The limitations of these figures are usually pointed out by calling attention to the many kinds and mixtures of the materials and the impossibility of applying specific rules to all cases. It is usually further emphasized that an ample and varied experience in foundation work is necessary before any definite allowable pressures for the foundation can be selected. These qualifications make it plain that at best only an approximate estimate of the bearing power of the soils can be made because of the lack of test data upon which more precise estimates may be formulated.

In the early years of highway construction in this country these figures for the bearing power of foundations for bridges were assumed to be applicable to highway subgrades in lieu of more pertinent information. In a vague way this grading did represent the relative

[5] Many soils make good subgrades which might not meet the requirements of a sand-clay or topsoil road.

[6] Procedure for testing subgrade soils, by J. R. Boyd, PUBLIC ROADS, vol. 6, No. 2, April, 1925.

[7] Practical field tests for subgrade soils, by A. C. Rose, PUBLIC ROADS, vol. 5, No. 6, Aug. 1924

Field methods used in subgrade surveys, by A. C. Rose, PUBLIC ROADS, vol. 6, No. 5, July, 1925.

bearing power of the subgrades but a more critical analysis in the hope of a more detailed differentiation led highway engineers to the conclusion that below the sands and through the clay there is a wide difference in soils caused by their character as well as the size of the soil particles. This difference affects the amount of swelling or shrinking of the soil with variations in moisture content and apparently also the amount of heaving when subjected to freezing.

The California study of the Bureau of Public Roads.—The question immediately arose as to what characteristic of a soil determined whether it would make a good or bad subgrade. One of the first attempts to solve the problem in a scientific manner was made in connection with the study of the California highway system by the United States Bureau of Public Roads in 1920.[8] The soils in this report were classified as follows:

(1) Clay and adobe soils (includes clay, silty clay, clay-loam, and clay).

(2) Marsh lands (includes salt, marsh, and peat lands).

FIG. 1.—Shrinkage cracks in the adobe soil in the open field adjacent to the Pittsburg test road were large enough to admit the arm halfway to the elbow

(3) Loams (includes loam, clay-loam, silt-loam, and silty clay-loam).

(4) Sandy loam (includes coarse sandy loam and fine sandy loam).

(5) Sand, and sand and gravel.

Crack surveys were made of the pavements and on this basis they were classified as to their relative condition. The report concluded that 70 per cent of the defective pavements occurred on adobe soils. A typical failure on the adobe soils consisted of the drying out and shrinking of the subgrade under the edge of the slab because of the evaporation due to the hot, dessicating summer winds. Traffic then broke down the unsupported cantilever of the pavement with the result that longitudinal cracks at the third point of the pavements were characteristic for long distances. As stated by the report, "Typical longitudinal (and other) cracking found on adverse subgrade soils, and shown by many of the 7,500 photographs now on file in the Bureau of Public Roads, indicates a distortion of the subgrade due to varying moisture content and shrinkage. The diagrams showing lines of equal moisture content clearly indicate the influence of the concrete pavement in preventing evaporation. The high capillarity of adobe soils and the great shrinkage in the long, hot summers thus produce very unfavorable conditions for a thin pavement under increasing traffic."

While this report recorded a decided forward step in the development of a classification of subgrade soils, it did not point out the fundamental characteristics of the soil which determined whether it would make a good or bad subgrade. The tests made on the soil samples included the standard moisture equivalent test used by Briggs and Shantz and volumetric shrinkage tests with the samples wetted to about capillary saturation. An analysis of these shrinkage tests shows that in general the values increase with the moisture equivalent percentage but there is a wide range in the values for the same percentages of moisture.

The progress in subgrade investigation which marked the California study may be summarized as follows:

(1) A definite classification of soils with respect to their suitability for highway subgrades was made upon the basis of soil types.

(2) Tests were made to determine the moisture content, moisture equivalent and volumetric shrinkage percentages of subgrade soils.

(3) The moisture equivalent percentage was indicated to be a critical value in respect to the bearing power of the soil.

(4) Seventy per cent of the defective pavements were shown to have occurred on the adobe soils. (fig. 1.)

(5) Typical longitudinal (and other) cracking found on adverse subgrade soils indicated a distortion of the subgrade due to varying moisture content and shrinkage.

The California study did not suggest any method for identifying poor subgrade soils nor did it develop any means of identifying the fundamental characteristics of a soil which determine its value for a highway subgrade. It did give, however, observed test values for subgrades which had been previously expressed only as generalities or at best in a much less specific manner. Of the earlier contributions to the subject, one of the most valuable was the excellent paper entitled "Water and the Subgrade."[9] The writer outlines in detail the necessity and reasons for adequate subgrade drainage, shows that capillary water, because it is unaffected by gravity can never be removed by tile drains, describes what may possibly be the natural processes which take place when soils freeze, and among other things urges the necessity of testing subgrade soils and using in the subgrade only those soils which meet certain recognized requirements. One of the most important statements in the article is that: "The obvious remedy for this condition of affairs (the plasticity or inadequate bearing power of clay soils with capillary moisture present) is to use less clay in highway subgrades."

THE MOISTURE EQUIVALENT PERCENTAGE CRITICAL IN RESPECT TO BEARING POWER

In the California study samples of the soil containing varying percentages of moisture were tested in the laboratory of the Bureau of Public Roads with uniformly increasing loads applied through a bearing block 10 square inches in area and the corresponding penetrations were measured. The statement was made that "* * * the moisture equivalent percentage is a critical percentage in respect to bearing power." While this is

[8] Report of a study of the California highway system by the United States Bureau of Public Roads. Issued 1920. Revised 1921. Government Printing Office.

[9] Water and the subgrade, by J. L. Harrison, PUBLIC ROADS, vol. 1, No. 12, April, 1919.

in accord with the other findings of the Bureau of Public Roads at the Arlington Experimental Farm,[10] it does not mean that soils with a moisture content in excess of the moisture equivalent percentage do not have sufficient bearing power to support reasonable loads. It does mean, however, that the bearing power of the soil falls off rapidly when the moisture equivalent percentage is exceeded. A more recent determination of this characteristic by the Bureau of Public Roads may be seen in Figure 2. The soil sample has a moisture equivalent percentage of 25.4. With increments of moisture up to 25.5 per cent there is very little increase in the penetration. An additional 4.3 per cent, however, which makes a total of 30.8 per cent of moisture, makes for a decided increase in the penetration, and further increments of water cause the penetration to increase rapidly.

POSSIBILITY OF CONTROLLING MAXIMUM MOISTURE CONTENT IN A SUBGRADE SOIL

The field investigations of the Bureau of Public Roads indicate that there is a possibility of controlling the moisture content of a subgrade soil to the moisture equivalent percentage as an approximate maximum value. Observations in the Pacific Northwest[11] generally indicated that the moisture content percentage was greater than the moisture equivalent percentage in the subgrade soils under recent failures in pavements but that the reverse was true when the pavements were in good condition. It was also found that a Cove clay soil, in the open field before any pavement had been laid and where the surface drainage was good, showed a moisture content less than the moisture equivalent percentage at a point 6 inches below the surface (to offset the effect of surface water) and immediately after heavy winter rains. It was considered possible, therefore, that a condition which existed naturally might be reproduced in a subgrade soil by a proper pavement and subgrade design. The natural soil seems to absorb water up to the moisture equivalent percentage and the balance runs off if the surface has sufficient slope for drainage. On the contrary, the pavement when placed on a soil acts as a roof which sheds rain water that does not leak through the cracks which develop in the pavement. The pavement, however, retains two kinds of water which wet the subgrade from below: (*a*) Water of condensation which is precipitated upon the lower side of the slab and falls back upon the subgrade; (*b*) water derived from "needle ice" which melts and runs over the subgrade. It seems hopeful that a pavement design may be adopted which will prevent an accumulation of water in the upper layer of the subgrade soil which is in excess of the moisture equivalent percentage.

The investigations of the bureau indicate that the subgrade soil at depths below the surface sufficient to eliminate the effect of surface water, generally has a maximum moisture content throughout the year which does not exceed the moisture equivalent percentage. The importance of this possibility of water control in the subgrade is apparent because the moisture equivalent percentage also seems to be the critical percentage in regard to the bearing power of a soil. Sufficient data have not been collected to formulate this as a general observation for the country at large but it has been found to be generally true in the States of Oregon and Washington where the freezing temperatures are infrequent, in Minnesota during freezing conditions, and at the Arlington Experimental Farm in Virginia where alternate freezing and thawing occurs. In many of these cases, however, the surface of the poorly drained subgrade soil was found to contain moisture in excess of the moisture equivalent percentage and even to complete saturation. The California study also was significant in showing the moisture equivalent percentage as the maximum for the subgrade soil in the lower depths. The moisture contents seemed to increase with the moisture equivalent percentages of the soil. Of 103 soil samples which were tested, only seven samples showed a field moisture content in excess of the corresponding moisture equivalent percentage and in only one of these cases was this difference greater than 2½ per cent. This applied to samples taken near the surface as well as at considerable depths. These investigations were made during the summer months and there is no direct evidence to show that the maxi-

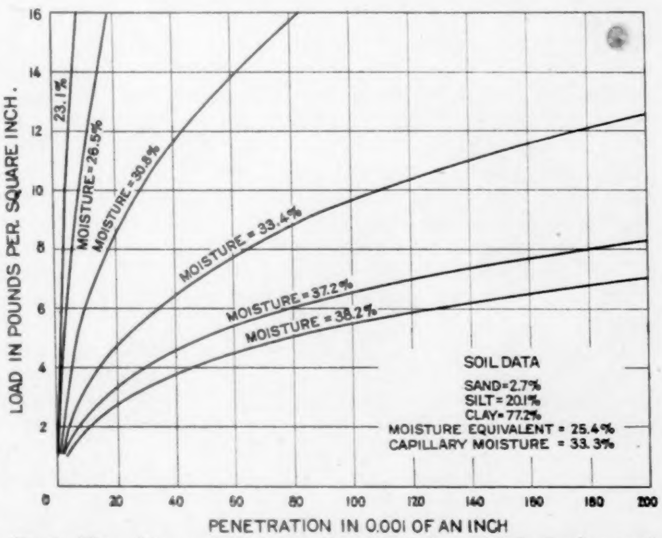

FIG. 2.—The moisture equivalent percentage seems to be a critical value in respect to bearing power. The bearing power falls off rapidly when the moisture content is made to exceed the moisture equivalent percentage

mum moisture content during the winter did not exceed the moisture equivalent percentage in a number of cases. In the California study, however, 49 of the 103 soils were sampled at a depth of more than 3 feet. Although the excessive evaporation in California would tend to increase the depth beyond which the moisture content remains uniform, the comparison of these figures should be interesting. Of these 49 samples, in only 3 cases did the moisture content exceed the moisture equivalent percentage. In one case the excess was 2.3 per cent, in another 2.2 per cent, and in the last 1.4 per cent. The California study lends strength to the observation that the moisture content of a well-drained subgrade may possibly be controlled below the moisture equivalent as a maximum.

Experiments were made by the Bureau of Public Roads[12] to determine whether it was possible to control the moisture content of a subgrade by various means, such as tile drains and cut-off walls and various subgrade treatments such as gravel subbases and water-gas tar. These experiments apparently yielded negative results although they confirmed the

[10] Physical properties of subgrade materials, by J. R. Boyd. Proceedings of the American Society for Testing Materials, vol. 22, 1922, Pt. II, pp. 352-353.
[11] Practical field tests for subgrade soils, by A. C. Rose, PUBLIC ROADS, vol. 5, No. 6, August, 1924.
[12] Subgrade drainage tests yield interesting preliminary data, by Ira B. Mullis, PUBLIC ROADS, vol. 4, No. 6, October, 1921.

findings of other experimenters that tile drains remove free water from the subgrade but not capillary water. The observed moisture contents of the first four of the 10 treated subgrades throw light upon the possible maximum seasonal limit of the moisture content of a subgrade, although moisture equivalent values were made only upon similar samples taken at the sides of the slabs and not upon the same samples for which moisture contents are shown.

In the first four cases there was used either no treatment as in the first, a subbase combined with tile drains as in the second case, or gravel subbase alone as in the third and fourth sections. In the first case without tile drains or subbase the maximum moisture content 6 inches down from the base of the pavement was 23.4 per cent. Moisture equivalent percentages adjacent to the same slab varied from 16.2 to 17.4 per cent and capillary moisture percentages from 26.6 to 35.7 per cent. In the second case the maximum moisture content 6 inches down from the base of the subbase was 22.6 per cent and moisture equivalent values in the nearby soil varied from 17.0 to 20.9 per cent and the capillary percentage from 26.2 to 35.4 per cent. In the third case the maximum moisture content 6 inches down from the base of the subbase was 21.8 per cent and moisture equivalent values in the soil adjacent to the test slab were 13.5 to 21.5 per cent and capillary percentages from 33.3 to 41.9 per cent. In the fourth case the maximum moisture content 6 inches down from the base of the subbase was 23.7 per cent and moisture equivalent values made, as in the first three tests, varied from 13.2 to 18.4 per cent and capillary percentages from 31.2 to 32.4 per cent.

Only in the case of the untreated subgrade did the maximum moisture content at the 6-inch depth exceed greatly the moisture equivalent percentage and even in this case, as in all the others the maximum moisture content of the subgrade during the entire season was closer to the moisture equivalent percentage than to the capillary percentage. Six inches below the subbase was considered representative in order to avoid the effect of surface water seeping under the pavement and excessively wetting the upper layers of the soil. The effect of frost in causing an increase in the moisture content of the soil near the under side of the pavement is evidenced by the tests only in the first case. The results strongly indicate that it should be possible to control the maximum moisture content of the subgrade very closely to the moisture equivalent percentage by subbases or tile drains.

STABILITY RATIO AS AN INDEX OF BEARING POWER

Defining the term *stability ratio* as the actual moisture content percentage of the soil divided by its moisture equivalent value, the field investigations of the Bureau of Public Roads in Oregon and Washington seem to indicate that the bearing power of a soil is relatively low when the stability ratio is greater than unity and, conversely, that when the stability ratio is less than unity, subgrades are generally well compacted, firm, and hard. The application of this criterion is limited to soils with moisture equivalent percentages greater than 20, but such soils have been shown by investigation to be, in general, the only ones of the suitability of which there is any doubt.[13] Whether the stability ratio is more or less than one can be easily determined by the ease or difficulty with which a drill penetrates the soil. When less than unity, the drillings come from the ground in hard, shiny spirals; when more than unity, the soil is generally soft and sloppy or putty-like, and the drill may be pushed down without rotation. Under new pavement failures in the Pacific Northwest the stability ratio was found to be almost invariably more than unity. This observation is full of potential possibilities. Certainly a marked advance in the progress of highway subgrade evaluation would be made if it were definitely shown that the maximum moisture content of a well-drained soil could be controlled and maintained below the moisture equivalent percentage at all seasons of the year.

It is interesting to note that a relation quite similar to the stability ratio was established in the subgrade laboratory of the Bureau of Public Roads and called the *moisture index*.[14] The relation was expressed as follows:

$$(1)\quad \text{Moisture index} = \frac{\text{volume of moisture}}{\text{volume of voids in soil}}$$

Based upon data determined in the laboratory, it was found that when the moisture index of the soil is less than unity, the bearing value was high, but low when the relation was more than unity except in instances where the dye absorption number of the soil was high.

It should be interesting to compare the equation (1) with the stability ratio, which is expressed as follows:

$$(2)\quad \text{Stability ratio} = \frac{\text{moisture content percentage}}{\text{moisture equivalent percentage}}$$

THE RECENT TREND OF ENGINEERING OPINION

It might be well to add here that for many years engineers have recognized the adverse effects of clay in subgrades without evolving any adequate method to evaluate the character and quantity of the clay present, or to determine the degree to which it would affect the stability of the road surfacing, or without attempting to arrive at an adequate surfacing or pavement, subbase or drainage design to overcome the trouble. Citations to the mass of data which have been piling up throughout the years as evidence of the effect of the character of the subgrade are given here briefly to show that these observations are not original with any one engineer or any group of engineers nor are they confined to any single period. On the contrary, they have been made by representative members of the engineering profession throughout its entire history and, therefore, the composite conclusion which may be drawn from the testimony is based upon comprehensive as well as authentic information. For brevity and completeness only recent data will be referred to.

Life of railway trackage affected by character of subsoil.—An abstract of a report to the joint committee on life of railway physical property of the American Electric Railway Engineering and Accountants' Associations[15] presents some instructive data concerning soil

[13] Practical field tests for subgrade soils, PUBLIC ROADS, vol. 5, No. 6, August, 1924.

[14] Physical properties of subgrade materials, by J. R. Boyd. Proceedings of the American Society of Testing Materials, vol. 22, 1922, pt. 2.

[15] R. N. Wallis, Fitchburg & Leominster Ry., Fitchburg, Mass., and Martin Schreiber, Public Service Ry., Newark, N. J., chairmen. Presented at the annual convention in Atlantic City, N. J., Oct. 16, 1913. Engineering News, vol. 70, No 20, Nov. 13, 1913, p. 972.

as well as climate and their effect upon the foundation and drainage of railway property. "On no two separate properties are climatic and soil conditions so similar that the physical elements of such properties would not be affected differently. * * * Property in a mild climate would not be affected by the conditions met with in a cold climate. Wet and dry climates affect physical properties differently, as also do the different soils of different localities. Construction on a rock foundation has a physical life materially different from the construction on any less firm foundation. Two localities may have the same soil, but one is situated topographically so that it is easily subjected to adequate drainage, while the other may be almost impossible of drainage owing to its topography. This would also affect differently the physical life of each. Any attempt to establish the life of physical railway property based on climatic and soil conditions would result in as many different periods of life as there are properties under consideration."

Sand subbase prevents soil from working up into voids of macadam.—Another adverse effect of clay was brought out in a discussion before a meeting of the Boston Society of Civil Engineers, by John R. Rablin, chief engineer, park division, Metropolitan District Commission of Massachusetts.[16] "We have found, where we have a clay subgrade, that if we lay crushed stone or coarse gravel over it before laying our macadam, in a few years, if we have occasion to excavate, most of the stone seems to have disappeared and the clay to have come to the surface or mixed with the stone. This action is probably due to frost and moisture. We have also found that by covering the clay with a layer of fine sand before putting on the coarse gravel or stone, it will prevent that to a large extent." Here are data which not only describe a condition but also advocate a sand subbase as a method of correction. Experiments of the Bureau of Public Roads at the Arlington Farm confirm this as a practical subgrade treatment.

Cracking of pavements due to shrinkage of adobe soil.—The experience of the city of San Antonio, Tex., in laying pavements upon what appears to be adobe soil is of interest.[17] "The subsoil is a sticky, black material when wet and it cracks in drying, with the result that the concrete usually cracks too. When the dried soil again takes up water it swells an appreciable amount. Successive wetting and drying enlarge even a hair crack in the pavement surface into wide breaks * * *." This exemplifies the shrinking and swelling of heavy clay soils with variations in moisture content. A similar condition was noted by the writer in the city of Rio Vista, Calif.

Excessive heaving by frost in clay soils.—The excessive heaving in clay soils due to freezing is outlined in an article by Stephen Taber[18] in which it is stated that "in a middle west city 16-ton concrete piers resting on 'solid blue clay' were elevated 3 inches during the unusually severe winter of 1916–17, and that subsequently they settled back to their original position." The theory had been advanced that this lifting was due to the hydraulic pressure resulting from the progressive freezing of the ground from the surface downward. Since the frost could not have penetrated more than 6 inches to 1 foot below the bottom of the piers and the expansion of this depth of water would not be sufficient to account for the 3-inch heave, Mr. Taber points out that this theory is inadequate because the specific gravity of the concrete is greater than that of the earth and, therefore, if there were any hydraulic pressure it would be expected that the frozen crust of the earth would be forced up rather than the concrete.

Mr. Taber states that the hypothesis of the soil being acted upon by a force similar to hydraulic pressure does not offer an adequate explanation of the phenomena. On the contrary he explains the case on the basis of his experiments which showed the pressure[19] exerted by growing crystals of ice. The following excerpts from his discussion are of singular interest to highway engineers:

"In the course of some of the writer's experiments, carried out on cold nights, weights placed on wet clay were lifted through the gradual formation of virtually pure ice between the weights and the clay. Weights that were similarly placed on wet sand were not lifted, or at least their elevation was imperceptible, and no pure ice was formed under the weights, although the water occupying the interstices between the sand grains was frozen.

"Water in extremely small capillary spaces remains in a liquid state at temperatures much below freezing. Most of the interstices in clay are in the form of very small capillary spaces, while in sand they are much larger. Therefore, the interstitial water freezes much more readily in sand than in clay.

"In the experiments referred to above the weights cooled off rapidly, thus chilling the film of water in contact with their lower surfaces until ice began to form. Where the weights rested on wet sand freezing gradually continued downward, thus firmly cementing the sand grains together. The grains of sand were slightly separated in places as a result of the freezing, but the total elevation of the mass was so slight as to be imperceptible. Where the weights rested on wet clay, however, the ice forming at the surface gradually increased in thickness because of the freezing of additional water that slowly reached the surface of the clay through the small capillary openings. Because of its manner of growth the ice had a fibrous texture, and as additions were made to its lower surface the ice was slowly elevated, together with any weights resting upon it.

"The ice columns, or 'needle ice,' formed on bare clay soils are familiar to most people living in regions where the nights are cold enough for heavy frosts. These ice columns, which commonly support sand grains, pebbles, and sometimes larger objects, are formed in the manner explained above; and all of the facts cited * * * indicate that the elevation of the concrete piers was probably due to this same process. If the piers had rested on sand instead of clay it is improbable that any elevation would have been noticed, no matter how thoroughly saturated with water the ground may have been.

"The elevation of the weights in the writer's experiments is not to be explained by attributing it to the

[16] A detail of road foundations in clay, Engineering News-Record, vol. 88, No. 11, Mar. 16, 1922.

[17] Texas soil requires paving base to be reinforced, Engineering News, vol. 75, No. 14, Apr. 6, 1916.

[18] State geologist and professor of geology, University of South Carolina. "Ice forming in clay soils will lift surface weights," Engineering News-Record, vol. 80, No. 6, Feb. 7, 1918.

[19] Pressure phenomena accompanying the growth of crystals. Proceedings of the National Academy of Sciences, vol. 3, pp. 297–302, April, 1917.

expansion in volume, which occurs when water freezes to form ice, for the distance through which the weights were lifted was approximately equal to the total thickness of the ice. The lifting of the weights was due to the growth of the ice crystals, and this would continue in spite of the pressure as long as water was available for growth and the temperature was low enough to cause freezing. With any increase in pressure, however, a lower temperature would be required in order that freezing should continue, for the melting point of ice is raised by increasing the pressure or in any way placing the ice under additional strain." These very interesting observations of Mr. Taber's indicate strongly that the greatest heaving due to freezing occurs on clay soils.

Frost-heaving phenomena of two classes.—These experiments, however, do not offer an explanation of the phenomena of heaving under pavements. There are two general types of these phenomena. The first is a progressive lifting of the pavements as the winter advances and the penetration of the frost increases in depth. This happens principally in sections of the country where extremely cold winters are the rule, such as Minnesota, and where the thermometer only occasionally rises above the freezing point after the cold weather has set in until the spring thaw begins. In this case the pavement gradually subsides into its original position when the frost gradually leaves the ground, and if the upward movement has been uniform and there has been no warping of the surface there seems to be little cracking due to the freezing. Unfortunately this uniformity of subgrade is rarely found and warping often occurs. For this reason cracking is generally the rule under this condition of heaving. The second condition is found in the Eastern States where the temperature throughout the winter rises and falls periodically above and below the freezing point. After a long thaw and usually in the spring there may come a severe drop in temperature. The result is that freezing occurs first in the earth shoulders between the ditches and the pavement and seems to progress inward toward the center of the road. It seems possible that the free water and moist subgrade under the center of the pavement is the last portion to freeze and in expanding rapidly exerts pressure upon the surrounding subgrade and the pavement above. Since the subgrade is more stable than the pavement the latter is heaved and broken badly over night. Observers who have seen this condition testify to mounds of ice which have been seen under the pavement at the heaved sections. These mounds are believed to have been caused by the outrushing water from under the pavement which froze immediately after the pavement was heaved and the pressure released.

Examples of the first or gradual type of heaving seem to have been furnished by the observations on existing pavements in Minnesota made by the Bureau of Public Roads which showed the progressive lift of the pavement at the end of the season to have reached a maximum height in some cases of 7 inches.

The condition of rapid heaving is ably discussed in a paper published in the Engineering News-Record.[20] "If the pressure is relieved by an outpouring of water only," according to this writer, "the pavement will settle back in place when the ground thaws out in the spring. Unfortunately, however, the water often carries with it enough solid matter so that the bunch formed at the point of rupture will not completely disappear."

Experiments by the Bureau of Public Roads show that there is a greater percentage of water freezable in sands than in clay.[21] This does not mean that the amount of heave in sands due to freezing will be greater than in clays. On the contrary, it would seem that the greater heaving would occur in clay with capillary water present because of the greater total amount of water frozen. Further experiments are needed to determine the relative heaving of coarse and fine-grained soils with varying moisture content.

Vertical displacement of concrete pavements by frost heaving of subgrade.—In a paper advocating the use of cut-off walls under the edge of a pavement to control the variation in moisture content of the subgrade, given before a convention of the American Concrete Institute, John W. Lowell, division engineer of the Universal Portland Cement Co.,[22] makes some interesting observations with regard to the effect of heaving on the pavement. Investigations of the Bureau of Public Roads throw considerable doubt upon the efficacy of cut-off walls in controlling the subgrade moisture content; but the data presented with respect to heaving have considerable value, especially the following quotations:

"In climates where freezing occurs, it has been found from general observation of pavement slabs less than 60 feet in length, that the following is true:

"(1) Transverse cracks do not occur as frequently as longitudinal cracks.

"(2) For width over 18 feet, frequency of longitudinal cracks is apparently unaffected by width of pavement.

"(3) Cracks seldom occur in pavement lying on sand or well-drained porous subgrades.

"(4) On clay or heavy loam soils, longitudinal cracks are of frequent occurrence.

"(5) The more compact the subgrade soil, the more frequently cracks occur.

"(6) Cracking of pavements on clay or heavy loam soils can not be entirely prevented by artificial drainage."

A section of concrete pavement 32 feet wide, 10 inches thick in the center, and 7 inches thick at the sides was selected to make the tests. The base was 1:2½:4 pebble concrete and the wearing surface 1:1:1½ concrete. The reinforcement consisted of No. 27 triangular wire mesh fabric weighing 41 pounds per 100 square feet placed between the base and the wearing coarse. Precise levels and data on temperature and rainfall were taken. "From slab 1 to 38 the subgrade may be described as spongy, tough, compact clay; from 39 to 45, sand-loam with spongy understratum and compact crust; from 56 to 70, clay and loam with some fine sand, the ground being spongy with sand below; and from 79 to 86, the south end of the pavement, sand of more than 3 feet depth. * * * Out of 86 slabs, 56 cracked. Thirty-eight which cracked deflected at one or both points more than seven-sixteenths inch in the 32-foot width between outside points, 18 deflected less than seven-sixteenths inch and of these deflections eight were between three-eighths inch and one-sixteenth inch, while four slabs having as great deflection failed to crack. Six of the

[20] First frost is never responsible for cracked concrete roadways, by J. L. Harrison, Engineering News-Record, vol. 80, No. 9, Feb. 28, 1918.

[21] Percentage of water freezable in soils, by A. M. Wintermyer, PUBLIC ROADS, vol. 5, No. 12, February, 1925, p. 5.

[22] Impervious Bituminous Wall Suggested to Prevent Seepage Under Paving, Engineering News-Record, vol. 81, No. 5, Aug. 1, 1918.

10 remaining slabs which cracked, having maximum deflection of from three-eighths to three-sixteenths inch, evidently cracked from abnormal settlement of a portion of the subgrade below the original level. The cracking of four slabs, with maximum deflections between three-sixteenths and five-sixteenths inch, is hard to explain unless the deflection had been greater at some period between readings. Every slab reaching a deflection of more than seven-sixteenths inch cracked. Therefore, it is safe to assume that such deflection in 32 feet of width is sufficient to crack any pavement built in accordance with present specifications. It is also evident that even greater deflection than seven-sixteenths inch can be expected when the subgrade is clay or loam with no other protection than underdraining. From study of the data collected it was shown that practically no longitudinal cracks occurred where the deflection was less than eleven thirty-seconds inch, and that where the subgrade has a uniform moisture content the deflection would probably never reach this figure, which conclusion is substantiated by those slabs which were over the sand subgrade."

"Thirteen consecutive slabs at the extreme south end of the pavement and on a sand subgrade acted quite differently and more uniformly than the others. The average upward movement was seven-sixteenths inch on the west side and $1\frac{1}{16}$ inches on the east side, while the center rose thirty-one thirty-seconds inch. However, the movements were so uniform that the greatest deflection was one-eighth inch and no cracking occurred. Unlike the other slabs, there was practically no settlement below the initial reading, the greatest settlement recorded being three thirty-seconds inch.

"The movements of two typical slabs, together with the rainfall and temperature, are shown in the charts. (fig. 3.) Upon freezing, the sides and centers of these slabs at first began moving up uniformly. During cold weather considerable snow fell, and then in the first week of January a thaw occurred, followed by extremely low temperature for the next eight weeks. In this period the sides of slab 18 on clay subgrade rose more rapidly than the center, until a maximum deflection of five-eighths inch occurred, while slab 86 on sand subgrade rose only six-tenths as high, there being practically no deflection. These concrete slabs were exactly alike, and precipitation and temperature were the same, the only difference being in the character of the ground on which they lay."

Mr. Lowell's explanation of the phenomena of heaving follows: "Upon freezing, the soil expands in proportion to the moisture contained, and the greater the difference in moisture between the sides and the center the greater the distortion of the pavement slabs. When a thaw occurs, if the soil is not fully saturated, the water sinks and spreads out under the pavement as far as it can go by virtue of head and capillary power. This moisture settles in until it freezes in the voids at some depth where the temperature is still below freezing. In this way an impervious stratum is formed through which the water will not pass. The later seepage is retained above this stratum, and the soil rapidly becomes more water soaked. With the return of colder weather and subsequent freezing of all moisture this subsoil expands, and, being restrained laterally, the pavement is heaved. Naturally, the vertical movement or heaving is greatest at the sides where moisture is at a maximum."

Mr. Lowell brings out clearly the amount of heaving due to freezing in a soil of high clay content, describes accurately the increase in vertical movement with a progressive drop in temperature, and shows that a center deflection of seven-sixteenths inch in the concrete slab 32 feet wide is sufficient to cause a longitudinal crack to form. The explanation of the phenomena of freezing, while probably sufficient for this particular problem, does not explain the matter satisfactorily where physical conditions are different and where the heaving is by a rapid rather than by a slow progressive lift.

It is unfortunate that most of the articles bearing upon the subject of heaving of pavements are discussions of the possible process of the heaving based upon experiments made in connection with other structures

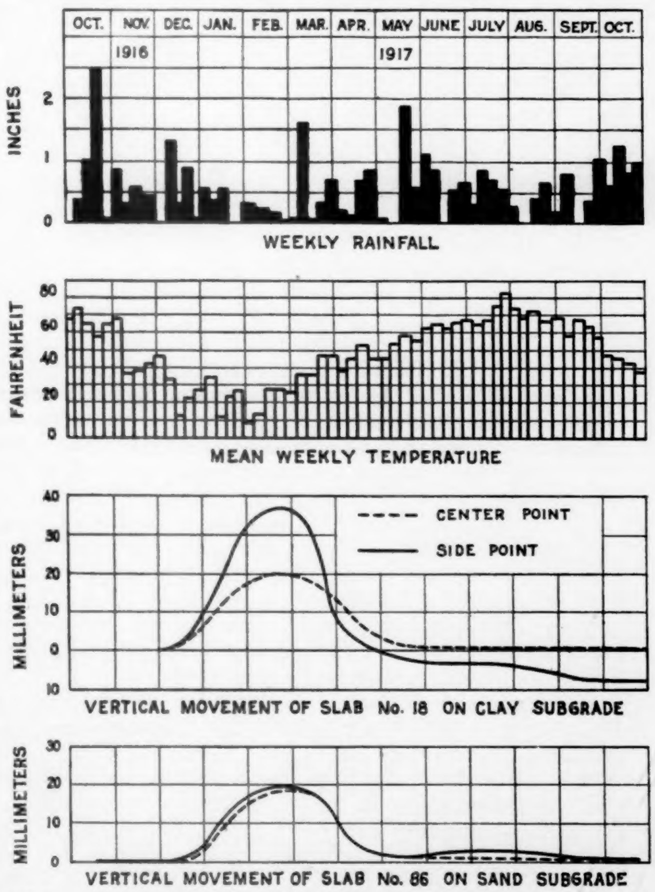

FIG. 3.—Climatic statistics and comparison of the vertical movement of a concrete pavement on clay and sand subgrades due to freezing

than pavements or are discourses premised upon heaving data rather vaguely expressed by a second party. At this time there seem to be no authentic data available as to the progressive stages in the freezing of the subgrade and the heaving of the pavement. The problem will never be satisfactorily solved until some research organization carries on a series of intensive studies on existing pavements. Such studies should include the raising of the pavement slabs and the making of photographs of conditions underneath throughout the winter when the frost lift is gradual, and up to, through, and after the period when the thaw causes the break-up of the pavement. Precise level readings at all stages would be invaluable. Until

some work of this character is carried on there seems little hope of arriving at an intelligent or satisfactory solution of this problem.

Operation of tile drains affected by permeability of soils.—The permeability of soils is discussed in an interesting article[23] in which it is shown that the porosity of the soil increases with the size of the grains. *M* is defined as "the quantity of water that would be transmitted in a unit of time through a cylinder of the porous medium, one unit in length, one unit cross-sectional area, and under one unit head or difference of pressure at the ends of and just inside the cylinder. *M* may be called the 'modulus' of the medium. * * *." The following figures are due to Professor Nazzani, of Rome:

Kind and size of material—Values of M in 24 hours

	Cubic feet
Small gravel (size about 2 mm.)	2,075
Coarse sand (size about 2 mm.)	224
Fine sand (size about 0.2 mm.)	40
Sandy soil	19
Sandy clay	10
Clay	2.8

The adequacy of tile draining for subgrades has been discussed pro and con by highway engineers for some time. The opinion now seems to prevail that there are certain soils such as sands in which tile drains are unnecessary; there are others in which the porosity of the soil is sufficient to permit effectual operation of the tile drain, and others, principally the clays, in which the porosity seems to be so small as not to permit sufficient water to enter the tile drains to make them effective. There seem to be special cases in clay soils, however, where tile drains are valuable. Examples are drains installed on the uphill side of long slopes to prevent the softening of the subgrade by standing surface water, water in soil pores or seams, seepage, porous strata, and hydrostatic pressure. It is evident, however, from Professor Nazzani's table that it should be possible to determine the soil types in which tile drains would be effective by carrying on experiments on soils with different sizes of grains, the character of the grains remaining constant.

Bearing power of soils.—The relative bearing power of soils has been demonstrated by a number of tests made by the Bureau of Public Roads.[24] Curves are shown with the load in pounds plotted as ordinates and the penetration in inches as abscissae for six soil types with moisture equivalent values of 2, 10, 19, 23, 34, and 41 and respective percentages of clay by mechanical analysis of 2, 19, 26, 26, 38, and 57. In order to compare the relative bearing power of these soils with the sizes of the grains increasing in fineness from one sample to another, it would be necessary to select arbitrary loads in pounds with the soils wetted to the moisture equivalent percentage. Upon such a basis these test results show no increase in bearing power with decrease in the clay content. This should not be accepted as a definite conclusion, because the tests were limited in their scope and intended to explain the method of soil testing rather than to present experimental data as to the relative bearing power. A part of the article, however, is considered of sufficient significance to warrant quotation here: "Results of the tests would indicate also that the bearing power of most soils is not appreciably reduced by the addition of moisture up to the moisture equivalent. * * * When the soils become saturated beyond the moisture equivalent, however, a rapid reduction apparently takes place in bearing power, which usually disappears completely at or before the water-holding capacity of the soil has been reached. These general comments are given here simply to indicate possible existing relations and are in no sense definite conclusions, which manifestly can not be drawn without much additional study."

Depths of macadam varied with subgrade and height of fill.—An interesting contribution relative to the bearing of the character of subgrade soil, the depth of fills, and the density of traffic on the required depth of macadam surfacing was published by the Superintendent of Roads of Monroe County, N. Y., in 1920.[25] The data are not sufficiently detailed to be of any great value at the present time for design, but the method of attacking the problem shows the trend of thought toward a selection of surfacing based upon traffic, soil, and other subgrade conditions. The third variable, climate, which is essential for evaluating designs over the country at large, was omitted since the area involved was only New York State, where the climatic variations were relatively small. Table 1 and its accompanying remarks are quoted from the article.

TABLE 1.—*Recommended depths in inches of macadam for different conditions*

Class of traffic	Subgrade soil	Depth of macadam in cuts	Depth of macadam in fills — Depth of fills: Less than 1 foot	1 to 3 feet	Over 3 feet
		Inches	*Inches*	*Inches*	*Inches*
Class I	Coarse sand and fine gravel	9	9	9	9
	Clay-loam	12–15	12–15	10–12	10
	Heavy clay and quicksand	20–24	20–24	12–18	10
Class II	Sand and gravel	7–8	7–8	7–8	7–8
	Loam	9–12	9–12	9	8
	Clay and quicksand	15–22	15–22	12–15	9
Class III[1]	Sand and gravel	5–8	5–8	5–8	5–8
	Loam	8–12	8–12	8	7–8
	Clay and quicksand	15–22	15–22	10–15	9

[1] Under Class III, it is better to use the depth recommended for Class II and reduce the width of metalling, if economy is desired, as all improved roads are bound at times to be subjected to the extreme loading produced by heavy trucks.
Class I. Large volume of ordinary vehicles and heavy auto trucks.
Class II. Large volume of ordinary traffic; a few heavy trucks.
Class III. Moderate volume of ordinary farm loads; very few heavy trucks.

The writer recognizes in a general way the necessity for an increase in thickness with increasing clay content of the soil and specifically a decrease in thickness with an increase in the depth of the fill because of the improved drainage conditions.

Hair cracks in concrete pavements on loess soil eliminated by tar paper.—An example of a loess soil causing hair cracks in a cement concrete pavement during the process of curing is reported by R. W. Crum, engineer of materials and tests of the Iowa Highway Commission.[26] The soil runs about 20 per cent clay and 80 per cent silt according to the mechanical analysis of the United States Bureau of Soils. The lineal shrinkage is only 2.3 per cent and the moisture equivalent 21.9 per cent. This is an example of a soil with

[23] Wells and permeability of soils, from Engineering, London, Dec. 31, 1920. Engineering and Contracting, Mar. 30, 1921, p. 312.
[24] Tests for subgrade soils, by A. T. Goldbeck, PUBLIC ROADS, vol. 4, No. 3, July, 1921.
[25] Variable designs for county highway systems, Engineering News-Record, vol. 84, No. 5, Jan. 29, 1920.
[26] Tar paper on loess subgrade lessens hair cracks in concrete pavement, by R. W. Crum. PUBLIC ROADS, vol. 6, No. 6, August, 1925.

a small clay content which does not shrink, swell or heave sufficiently to cause extraordinary trouble after a concrete pavement is completed but which causes hair cracks to develop in the concrete pavement during the period of construction. The hair cracking was overcome by interposing a layer of tar paper between the subgrade and the pavement during construction.

The explanation for the physical phenomena is not given. The angular shape of the grains and the large percentage of voids in a loess soil, may cause rapid capillary action with the result that the water in the fresh concrete is withdrawn before the crystallization of the concrete has reached completion. This would cause a shrinkage of the concrete with the result that hair cracks would develop. Climatic conditions such as wind and a low relative humidity of the atmosphere might contribute to the formation of the hair cracks. The grading and character of the sand and coarse aggregate might also reduce the rententivity of the concrete to water. Whether the cracking in this case is due entirely to soil conditions or to a combination of causes should furnish an interesting subject for further investigation. At least the methods adopted for the Iowa loess soil should not be used elsewhere without thoroughly checking against the local conditions.

It is of prime importance to note at this time, however, that the experiments of Mr. Crum as well as his observations on completed pavements show that the use of tar paper on the subgrade has been effectual in practically eliminating hair cracks.

Selection and redistribution of subgrade soils.—The selection and redistribution of soils to secure a stable subgrade is a possible method of construction. The general practice however is to place a granular subbase upon the undisturbed subgrade soil. This has been accomplished to a certain extent by the method of stage construction practiced in the Southeastern States. There pavements have been constructed on old topsoil roads. The topsoil therefore became a subbase for the pavement or a subgrade with adequate and uniform supporting value which overcame the adverse effects of the bad subgrade soils lying beneath.

FIELD SUBGRADE INVESTIGATIONS OF THE BUREAU OF PUBLIC ROADS

Having presented representative data from various sources to show the trend of engineering opinion on the subject of subgrades, the discussion of the more specific subgrade investigations, begun with the California study by the Bureau of Public Roads, will be continued. The same bureau in April, 1920, began a field inspection of road failures produced by poor subgrade conditions with the idea of determining the proper design of pavement and subgrade. One result of this work has been the development of field tests for subgrade soils and the suggestion of a method for measuring the character of the subgrade.

A field test for the moisture equivalent percentage was developed which gave, for soils with a moisture equivalent percentage greater than 20, identical results with the amount of water retained by a soil sample in opposition to one thousand times the force of gravity by the standard centrifuge method. The test was believed to be valuable for determining the degree of fineness of the soil grains since soils with fine grains would have a larger total surface area than those with coarse grains and therefore the fine-grained soils would generally show a large moisture equivalent percentage. This is not always true because the moisture equivalent percentage varies with the character as well as the size of the grains and, therefore, whether the grains be glazed or rough, solid or porous, will materially affect the result. The character of the surface of the grains may affect the thickness of the water film on each grain; their texture affects their surface area and in that way their capacity to retain water, the more spongy the grain the greater the surface area. The character of the grains affects the moisture equivalent values to such an extent that it has never been found possible to develop an empirical formula for the derivation of the moisture equivalent from the mechanical analysis of the soil separates such as sand, silt, clay, etc. In general, however, the clay content of the soil increases with the moisture equivalent percentage.

The significant test developed in these field investigations was the lineal shrinkage test. It was considered desirable to determine this value because the vertical distortion or displacement of the subgrade resulting from the shrinking or swelling of the soil is a factor which limits the life of a road surface. From an investigation of the condition of a number of pavements coupled with an analysis of their subgrades the conclusion was reached that a lineal shrinkage of 5 per cent, equivalent to a volumetric shrinkage of 14 per cent, would represent the maximum value for a good subgrade soil. Soils with a moisture equivalent of 20 per cent or less were found quite generally to have a lineal shrinkage of less than 5 per cent and were therefore considered as good subgrade soils. Soils with a moisture equivalent between 20 and 30 per cent were classed as doubtful subgrade material because the lineal shrinkage in these cases often exceeded 5 per cent. When the moisture equivalent exceeded 30 per cent the lineal shrinkage generally exceeded 5 per cent, and these were considered bad subgrade soils. These studies were made in the States of Oregon and Washington, and the limits referred to may only be applicable to the soils of that general region. However the significance of the test is not affected by location, and its application and use in other sections would quickly determine the limits which should be set for each region.

From these investigations a method of making subgrade surveys for roads was developed which is varied according to whether the area traversed by the road project is covered by a detailed Bureau of Soils survey map, a reconnaissance map or is in an unmapped area. Where detailed soil maps are available it is only necessary to establish the location of the changes in soil types as shown on the maps with reference to the stationing of the road, and representative samples of the various soil types on the project may then be taken and tested. The results of the lineal shrinkage test are used to classify the soils as good or bad. In the Pacific Northwest, where the method originated a lineal shrinkage of 5 per cent is taken as the limiting value for a good subgrade soil; for other sections it may be necessary to develop other limits. This is the first comprehensive method [27] which has been advanced for the identification of the character of the soil in highway subgrades. It is not original except as applied to highway subgrades, having been used for many years by the United States Bureau of Soils to evaluate the agricultural value of various soil types.

[27] Field methods used in subgrade surveys, PUBLIC ROADS, vol. 6, No. 5, July, 1925

THE CONTRIBUTION OF THE PITTSBURG TEST

The two great field tests of pavements made at Pittsburg, Calif., and on the Bates Road in Illinois furnished additional but meager information on subgrade soils. The Pittsburg tests were made on a quarter-mile elliptical track containing 13 different types of cement concrete pavement on which traffic began on November 9, 1921; the Bates Road, a 2-mile tangent surfaced with 68 kinds of six major types of pavement, was subjected to traffic initially on March 30, 1922. The first test was carried on by the California Highway Commission and the Pittsburg Steel Co. cooperating with the Bureau of Public Roads. The second test was carried on entirely by the Illinois Division of Highways.

The Pittsburg test road [28] was built on California adobe, a black, sticky gumbo, common to that section of the country. As the construction of the subgrade was considered one of the principal features of the test, the sections of the report pertaining to the subgrade are quoted in part as follows:

"The site of the test highway was a field in which the soil was a very obstinate black adobe. The ground sloped gently from the south to the north and to avoid variations of subgrade condition the entire subgrade was on fill. On the south side, excavation was carried to 3 feet in side borrow pits and the material placed loosely outside and the fill for the entire track was then started approximately 3 feet below finished subgrade elevation. The bottom soil was first plowed about 8 inches to produce a bond, and layers of earth approximately 9 inches in thickness, loose, were successively placed from the borrow across the entire width of roadway, and each layer pulverized by using a disk harrow followed by straight-tooth harrow, and a Johnson scarifier. After pulverization was complete, a light spray of water was applied over each entire layer sufficient to moisten, but not excessively wet the soil, and to aid in compacting it into a dense homogeneous mass. A 12-ton, 3-wheel road roller rolled each layer, and weak spots in the subgrade layers that developed were excavated, and refilled, and rolling continued. The compacted layers were approximately 6 inches thick and each was scarified with a Johnson scarifier for 2 inches to furnish a complete bond with the succeeding layer.

"On this approximately completed subgrade, header boards were set true to line and grade and extending slightly below the surface. Then the material between was scarified to a depth of 6 inches by a Johnson scarifier. The surface was then graded with a Carr subgrade machine to an elevation approximately 1½ inches above subgrade. The surplus earth was temporarily placed on the shoulders. Then the subgrade was scarified to a 4-inch depth and water applied with a very light spray and immediately the subgrade was rolled from the edges inward. While still moist it was again cut with the subgrade machine to the correct elevation. Up to the time of laying concrete the subgrade was given a light sprinkling daily to prevent cracks forming. Where inverted curbs were involved in the design excavations were made with pick and shovel."

Moisture penetration believed combated by subgrade treatment.—The test traffic was begun with the side ditches dry. At the end of the first month (December 21, 1921) the ditches were filled with water to the bottom of the pavements. The report continues:

"This water level was maintained in the ditches until the traffic was discontinued January 30, 1922. However, the water was not drained away until the middle of March, 1922. It was anticipated that with the ditches full of water the grade would soon become saturated and the destruction of the pavement accelerated. The rains were also expected to contribute very materially to this result. This opinion seemed to be shared by visiting engineers who had experience with adobe under such conditions. The result did not meet the expectations. Only a very small amount of additional moisture was taken up by the grade. The moisture determinations of the borings indicated that beyond a lateral distance of 2 feet from the water the absorption was very small. This resistance of the grade to moisture penetration can be attributed to the manner in which it was built."

The foreword of the report points out:

"The satisfactory results obtained by the construction of the adobe subgrade in successive thin, rolled layers, lightly sprinkled, seems to warrant (especially on adobe soil) the additional refinement of this fundamental process, which has been somewhat neglected in recent years. Examination of the final distribution of moisture in the Pittsburg subsoil shows a surprising absence of penetration from the flooded ditches and further studies should determine if such impenetrability is permanent. Therefore this important indicated result of the test should be immediately verified by trials and study in actual construction under equally (or even more) unfavorable conditions."

In describing the moisture contents of the soil the report states:

"Samples of the soil were taken at intervals from the shoulders each side of the pavement and from holes that had been left in the pavement when constructed. Samples were taken of the top layer of soil and also at depths of 1, 2, 3, and 4 feet. These samples were removed from the subgrade by a 2-inch earth auger and immediately were placed in air-tight cans and shipped to the laboratory for moisture content determinations. * * * The variation of the moisture content of the subgrade during the period from December, 1921, to September, 1922, did not exceed 15 per cent."

Discussion of findings.—"The method of constructing the subgrade on adobe soil, as described, so reduced the objectionable features of this material that a reliable foundation for the pavements resulted." This was the first of the seven conclusions of the report. If further investigation proves the adequacy and economy of this method of constructing the subgrade, it should be possible to give it a wide range of usefulness in the adobe areas of the Western States. Its cost and the construction difficulties seem to weigh heavily against it. In California especially, longitudinal cracks at the third point are characteristic of pavements laid on adobe subgrades. These are caused by the adobe drying out and shrinking under the edges of the pavement. The cantilevered slab then breaks off under the traffic. The adobe shoulders on the Pittsburg test pavement were very wide and one foot and more above the top of the pavement in many places. It is possible that this soil layer dried out at the surface but, acting as a blanket, prevented the subgrade under the edge of the pavement from drying out and shrinking. If this observation has any merit it would discount to a large extent the conclusion that the

[28] Report of highway research at Pittsburg Calif., 1921-22, California State Printing Office, Sacramento, 1923.

method of preparing the subgrade prevented volume changes in the adobe soil. However, as the report states, the method has potent possibilities which seem to warrant a further and more intensive study of this particular feature.

BATES ROAD TEST IN ILLINOIS

In discussion of the Bates Road tests it seems best to quote from the report of Clifford Older,[29] under whose direction the test was carried on.

Subgrade believed to be of uniform character.—The uniformity of the soil on the project was described as follows: "Inasmuch as the soil throughout a large part of the State exhibits fairly uniform physical characteristics and considering the fact that the relative behavior of the various sections could not be judged if the nature of the foundation varied materially, a site was selected where subgrade conditions would be as nearly uniform as possible. Practically all unprejudiced observers agree that the Bates Road site fulfilled these conditions as ideally as could be expected on a length of road of two miles or more. No visible variation in the character of the soil could be detected; on the other hand, no positive method of establishing beyond question the lack of variation in subgrade soil could be found."

"Under each edge of a 200-foot section of the Bates Road was laid a tile drain 24 inches below the subgrade, the trench back-filled with cinders, and a free outlet provided for the tile. Moisture samples were taken from the underlying soil at various points throughout this 200-foot section, and likewise from the adjacent undrained slabs. During a period of three years, no measurable difference in the moisture content of the subgrade at these points has been observed. At another place, on the 'Chatham Road,' where clay of a different character is found, tile drains were laid 42 inches under each edge of the pavement for a distance of 1,000 feet, the trenches were back-filled with cinders, and similar extended observations were made, with results as shown on Figure 4. No attempt is made to explain why the soil underneath the section provided with tile drains has throughout the entire period contained more moisture than that under the adjacent pavement. Judging from these two examples in which tile drains were of absolutely no apparent value, it is questionable whether such attempts to control moisture are of any merit whatever in clay soils."

Subsequent moisture content of subgrade affected by amount of wetting during construction.—"It was found that both the brown silt-loam of the Bates Road subgrade and the yellow clay of the 'Chatham Road,' when they have a moisture content which may be considered normal for the summer months, resist further saturation to a marked degree. Attempts to saturate the soil underneath the Bates Road failed. Water standing at subgrade elevation for six weeks during the summer months did not cause a perceptible rise in the moisture content of the subgrade soil at a sampling station 30 inches distant. Tests now under way on 30 samples of clay soils, gathered from different points throughout the State, indicate that this phenomenom in slightly varying degrees probably is common to all.

"Another series of experiments indicate that if the moisture content of any of these clay soils is reduced to a point where the soil is dry enough to crumble readily, absorption takes place rapidly, to the point of saturation.

"These two properties of clay soils may have a marked effect on the supporting power of the subgrade under a freshly laid pavement slab; for example, the sections of the Bates Road built in the fall of 1920 were laid on a sun-dried subgrade, as a rainless period and hot weather had preceded the construction of the pavement. In October, 1920, the first moisture samples were taken from the underlying soil just after a three-day period of rain. At that time the subgrade was found to be as nearly saturated as it ever became. On the other hand, sections 64 to 68, inclusive, were laid in the fall of 1922, when the subgrade soil contained about 25 per cent moisture. The moisture content of the soil under these slabs remained practically constant throughout the winter months of 1922–23 and, although the spring and summer rains were heavy, it continued throughout the summer of 1923 materially below that of the remainder of the road. From this, it may be inferred that for perhaps a period of a year or more after the pavement is laid, the bearing power of a clay subgrade soil may be affected materially by its moisture content at the time of construction."

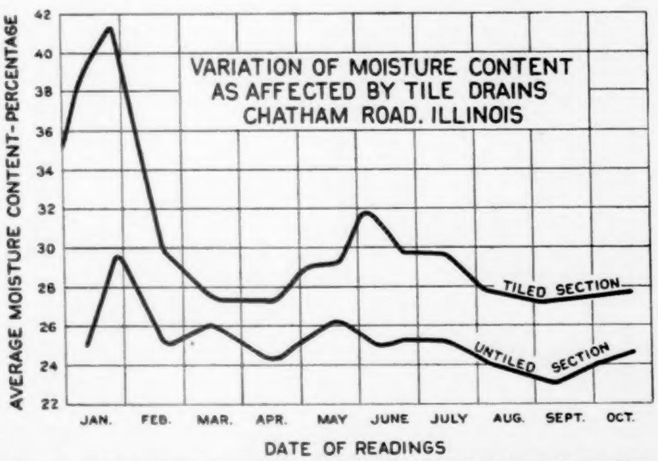

FIG. 4.—No explanation is available to show why the moisture contents of the subgrade on the tiled section were greater than those on the untiled section

In another section of the report the following statement is made:

"Many clay soils when dry, readily take up sufficient moisture to cause a high degree of saturation, but absorb water slowly when moist; hence, subgrades of dry clay should be moistened to a considerable depth by sprinkling before a pavement is laid. If the construction is on a dry clay soil, excessive saturation and minimum bearing values may occur before the concrete has attained normal strength."

Elastic properties of subgrade soil.—In order to test the elastic reaction of a subgrade under repeated deformations, a special apparatus was devised. As a result of the tests made with this device the following comment was made: "The results of these tests are not sufficiently complete to justify definite conclusions. Present indications, however, point to the probability that none of the clay soils exhibits sufficiently uniform elastic properties to justify an assumption of elastic subgrade supporting power for use in a design formula.

[29] Highway research in Illinois, Transactions of the American Society of Civil Engineers, vol. 87, 1924, pp. 1181-1224.

It is certain that, for purposes of pavement design, it is not safe to place reliance on a bearing-power test involving only a single application of load."

Discussion of findings.—The soil investigations of the Bates Road were valuable in that they further emphasized the truth of similar observations which had previously been made. That tile drains are not effective in a clay soil and that the bearing power of a subgrade soil may be affected materially by its moisture content during the time of construction were well-known phenomena prior to these tests. On the contrary the tendency of a wetted subgrade to resist further saturation, while a subgrade originally dry will later absorb moisture in excess of that present in the wet subgrade which resists further saturation is a feature which seems to have been given little, if any, previous attention. The practice of wetting subgrades before the pavement is laid has always been emphasized, although the serious consequences of a greater saturation which might result if the subgrade was not wetted, has never been particularly stressed. This is a procedure which should receive attention. Added to this is the probability that a dry subgrade will absorb moisture from a freshly laid concrete pavement and, becoming saturated, may distort and cause hair cracking of the pavement before the final set has occurred. Another novel section of the report on the subgrades was the investigation of the elastic reaction of the soil under repeated loads. Of course this elasticity applies to clay rather than to sandy soils, but the possibility of a lag in returning to original position after deformation certainly indicates further the uncertainty of clay foundations for subgrades.

RESEMBLANCE BETWEEN THE PITTSBURG AND BATES ROAD SUBGRADE FINDINGS

The heavy adobe soil under the Pittsburg test road with the predominating moisture equivalent percentages varying from 40 to 50 was believed to have been made more impervious to water by unique methods used in constructing the pavement. The construction was accomplished by excavating and backfilling the subgrade in layers and rolling and sprinkling the successive layers. This appeared to retard the rate at which the soil later absorbed water. Whether the subgrade would permanently take up less water because of the treatment was believed to be a subject for further study.

The brown silt-loam of the Bates test road with a moisture equivalent percentage of approximately 30 was found when wetted during construction with a percentage of water normal to the summer months, to resist further saturation to a marked degree. It was believed that this added resistance might extend over a period of one or two years and thus be of value in providing a more substantial subgrade to the pavement during the time when it was developing a permanent set. On the contrary the pavement laid upon the dry subgrade, absorbed water rapidly later in the season to the point of saturation. This maximum water content exceeded that of the soil originally wetted with an amount of water normal to the summer months.

The Bates and Pittsburg findings were similar in that the subgrades wetted prior to construction seemed to resist further saturation. This might have been due to the puddling of the soils and a resulting rearrangement of the soil clusters or grains so as to produce a greater density, thereby making the soil more impervious to water. Or the seams resulting from the cracking of the adobe soils when shrinking might have been eliminated when the soil was rearranged. This would do away with the seams as water-bearing channels to accelerate the saturation of the soil. It may be that the Pittsburg test method of rolling and sprinkling the subgrade in layers further accomplished the rearrangement of the soil grains and clusters by physical or mechanical processes. A similar cause may have produced the results noted in the Bates Road test but there is nothing to indicate this in the reports. The important point to bring out, however, is the possibility that the characteristics of a subgrade soil may be improved by physical or mechanical processes. As to this possibility there is further evidence in the experience of former city engineer, Burwell Bantz, of Chehalis, Wash. Mr. Bantz states that he found that sidewalks laid on heavy clay soils cracked badly. To overcome this he excavated the top layer of the clay subgrade, backfilled, and tamped it into place and sprinkled. The cracking of the sidewalks was found to be materially reduced.

SOIL BEHAVIOR IN PRESENCE OF MOISTURE ALTERED BY CHEMICAL PROCESSES

That the behavior of a soil in the presence of moisture may also be altered by natural chemical processes is indicated by the following quotations:

"The physical condition of the soil and particularly its permeability to water is largely influenced by the character of the bases that are combined with the soil. When the alkaline bases, sodium and postassium, predominate the soil is deflocculated and impermeable. When the earthy bases, calcium and magnesium, are in excess the soil is flocculated and permeable.

"When saline soils are leached to reduce the concentration of the soil solution it is often found that they become impermeable to water. This condition is due to the effect of the alkaline bases combined with the soil which causes deflocculation to take place when the salts of the strong acids, sulphate and chlorin, are removed from the solution."[30]

And "according to experiments of Gedroiz, the enhanced swelling of the soil and dispersion of the colloidal material take place after the excess of soluble salts is removed, the presence of considerable quantities of the sodium salts tending to keep the colloidal material in a flocculated condition."[31]

It seems apparent, therefore, that bad subgrade soils may be transformed into good subgrade soils by natural physical or chemical phenomena. These natural phenomena which produce a permanent transformation of the soil occur over long periods of time. The Bates and Pittsburg test results indicate that a temporary improvement in the subgrade soils may have been accomplished rapidly by artificial means. The improvement of the character of bad subgrades by accelerated artificial chemical processes provides a fertile field for further investigation. If the active elements in a heavy clay could be rendered inert by an inexpensive chemical means it would revolutionize our present methods of pavement design.

[30] The movement of water in irrigated soils, by Carl S. Scofield, Journal of Agricultural Research, vol. 27, No. 9, Mar. 1, 1924.

[31] Recent investigations of soil colloids, by Philip L. Gile. Proceedings of the American Society of Civil Engineers, vol. 51, No. 5, May, 1925.

BUREAU OF PUBLIC ROADS LABORATORY EXPERIMENTS AT THE ARLINGTON EXPERIMENTAL FARM

Coincident with this work done by other agencies the Bureau of Public Roads has been making investigations at the Arlington (Va.) Experimental Farm to determine the behavior of subgrade soils when acted upon by an external force and also to ascertain the characteristics of soil which determine the degree to which it will be affected by an external force or climatic conditions.

The most important of the investigations of the behavior of soils when acted on by external forces are described briefly in a recent paper published in the Transactions of the American Society of Civil Engineers.[32] This paper is quoted as follows:

"*Influence of the bearing value of the subgrade.*—The intensity of pressure on a road subgrade is governed by a number of factors. The wheel load is carried directly by the wearing surface which, in turn, transmits the pressure to the underlying subgrade. If the wearing surface is of a rigid type, as concrete, capable of resisting bending, the subgrade pressures are distributed over a comparatively broad area adjacent to the wheel, and the highest intensity of pressure is comparatively low. On the other hand, if the surfacing material is of a flexible type, incapable of resisting bending, the area of distribution of subgrade pressures will be quite restricted and the intensity of pressure under the wheel will be high. These statements are illustrated by curves of pressure distribution obtained under concrete and with broken-stone surfaces of equal thickness, both subjected to a concentrated load. (fig. 5.) The pressures were measured by soil pressure cells, described elsewhere.[33]

"The degree of yielding of the soil also affects the pressure distribution. Thus, a solid rock subgrade would have high and restricted pressures under the wheel load, whereas a soft soil would have low pressure intensities, well spread out, provided, of course, the overlying slab was of such a nature as to resist bending. The flexibility of the slab likewise controls the pressure intensity and distribution. Rigid slabs, such as concrete, can deflect little before a crack is produced; other types of pavements of less rigid character can be deformed more, without the accompanying incipient failure. The subgrade material, therefore, has to develop its resistance to the overlying load within safe limits of deformation of the pavement. It is quite important that the bearing value be obtained corresponding to a known amount of deformation of the subgrade. This amount will be less with rigid slabs than with nonrigid slabs."

The most important implication made by these data is the necessity for experimental studies to determine the bearing power of the various types of soils from gravel, through sand and silt to clay. These tests could possibly be made by gradually applied repeated loads (not involving impact) through concrete slabs to the various soil types each with degrees of moisture varying from the hygroscopic coefficient through the moisture equivalent percentage, to complete saturation. The critical load in the soil type would be determined when the soil fails to resume its original position (within reasonable limits) after deformation, while with further repetitions of the same load the deformation increases and the soil pushes out from under the slab and exemplifies the action of an unstable subgrade. By correlating the force of impact and statically applied loads it might be possible to determine a constant which might be used as a multiple of the observed critical load determined statically and the result would represent the limiting safe pressure which could be sustained by any soil type under the varying moisture conditions. Then by establishing the limiting value for the moisture content which should be permitted in a subgrade it should be possible to establish the greatest allowable pressure for any soil type as classified by the United States Bureau of Soils. Using a high factor of safety probably from 4 to 10 because of the variable character of soils, it might then be possible to arrive at the proper thickness of pavement of the various classes of broken stone, bituminous concrete and cement concrete, that it would be necessary to use in order to distribute the load over a large enough area to maintain the allowable pressure in pounds per square inch within the observed allowable pressure determined for the particular soil type after being divided by a high factor of safety.

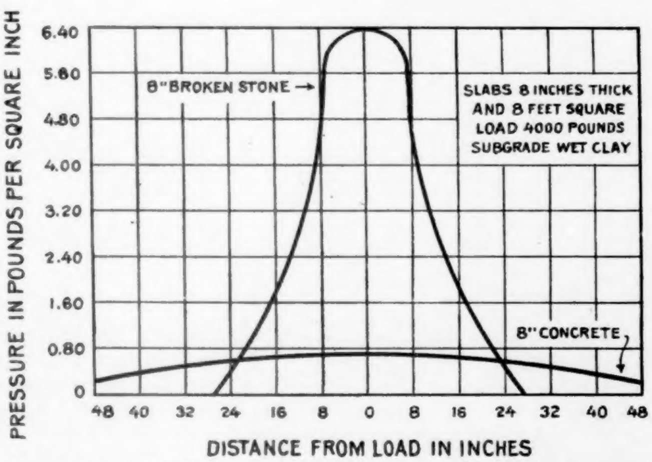

FIG. 5.—Pressure distribution to the foundation through broken stone and concrete slabs

"*Influence of bearing area on bearing value of soils.*—Another consideration in determining the bearing value of subgrades is that due to the different area of support offered by the subgrade, depending on the rigidity of the road slab. The bearing value of a soil, for a given penetration of the bearing area, depends on the magnitude of that area. It was with these considerations in mind that a series of tests was conducted to determine the influence of the size of areas on the bearing value of soils for definite penetrations of those bearing areas into the soil. These investigations were conducted, using bearing blocks of from several square inches up to 9 square feet in area, and with different types of subgrade materials, such as plastic clay and sand. Although there is some variation in the law for the different kinds of materials, the accompanying curve (fig. 6) is, in general, indicative of results obtained. It will be noted that when small bearing areas are used, the intensity of pressure required to produce a penetration of 0.1 inch far exceeds that for large-sized blocks. This is readily explained by the fact that when the large bearing areas are used a

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[32] Researches on the structural design of highways by the United States Bureau of Public Roads, by A. T. Goldbeck. Transactions of the American Society of Civil Engineers, vol. 88. p. 264 (1925).

[33] The distribution of pressure through earth fills, by A. T. Goldbeck, Proc. A. S. T. M., 1917.

greater thickness of the soil is compressed, which contributes more toward the movement of the block than in the case of the small bearing area. It may not always be possible to make bearing value determinations by the use of large-size blocks. If smaller bearing blocks are used, it will be necessary to obtain the bearing value of the soil at a much less penetration, in order to obtain values corresponding to a definite penetration of the large bearing block. The relation between the depths of penetration of different sized bearing blocks for like intensities of pressure has been established by a series of tests using various bearing areas."[34] In Figure 7 is shown the results of this investigation, giving the relative penetrations of the areas under equal intensities of load. The experimental results for a constant unit load equal to that which causes a penetration of 0.1 inch over the area of 9 square feet seem to be quite accurately expressed by the relation:

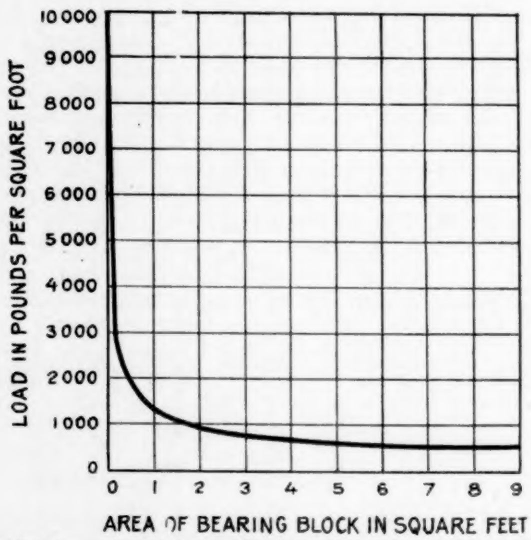

FIG. 6.—Relation of the unit load to the area of the soil bearing for a penetration of 0.1 of an inch

$$\text{Area (square feet)} = 900 \times [\text{penetration (inches)}]^2$$

From this equation, it follows that:

$$\frac{\text{Penetration } (a)}{\text{Penetration } (A)} = \sqrt{\frac{a}{A}}$$

in which, a and A are the areas of the respective bearing blocks. Other experimenters have confirmed this relation.[35]

In regard to these bearing value tests, some very pertinent observations may be made. If to produce a penetration of 0.1 of an inch with a bearing block 3 square feet in area it took a load of 800 pounds per square foot and with a bearing block of 2 square feet area 900 pounds were necessary, it would seem that the practice of reducing the size of the slabs in concrete pavements by transverse and longitudinal joints would reduce the stress in the subgrade. However, it is not believed that this is the case because the greatest stress in a pavement occurs at the corner of the slab and the amount of this stress would not seem to be diminished by reducing the size of the slab. It must also be remembered that these tests apply to a uniformly distributed load over the area and not a concentrated load or a blow delivered by impact. Further, that the limit of the comparative deformations in each case for the several loads was 0.1 of an inch. The tests also were confined to observations made to determine the relative penetrations caused by the same unit of load. The relative loads necessary to produce a common penetration were not studied. Mr. Goldbeck points out that it is possible that this relationship might change with progressively increasing deformations of the subgrade beyond the so-called elastic limit and specifically limits the results to the elastic limit of the soil and logically this limit would seem to be the extreme condition in the design of a subgrade. The facts brought out by this investigation apply especially to the design of footings for bridges. The investigation indicated that the current practice of assuming equal deformations of the foundation soil with equal intensity of pressure regardless of the total area of the footing is erroneous. On the other hand, in order to obtain an equal settlement of the footings, a method should be used which would vary the allowable pressure with the area of the foundations.

[34] Research on the structural design of highways by the U. S. Bureau of Public Roads, by A. T. Goldbeck, Trans. Amer. Soc. Civ. Eng., vol. 88, p. 274 (1925).
[35] See article in Le Genie Civil, May 26, 1923, by Bijls, of Belgium.

IMPROVEMENT OF SUBGRADES BY ADMIXTURES

To the question as to whether it is possible to convert a plastic type of subgrade into a more desirable nonplastic type through some system of curative treatment, the Bureau of Public Roads answers by giving the results of experiments made in its laboratory. Figures 8 and 9 show these results; and it is evident from Figure 8 that additions of 5 per cent of lime and Portland cement decrease the volumetric change due to variations in moisture content and increase the bearing power up to the limit of the capillary moisture capacity of the soil. The use of both lime and Portland cement is very expensive, and to determine the possibility of reducing the volume change of bad subgrades with a cheaper admixture, comparative tests were made on medium sand and Portland cement, the results of which are shown in Figure 9. It appears from these results that medium sand is more effective than Portland cement in reducing the volume change in bad subgrades. The difficulty, from a practical standpoint, of breaking up the clumps in a clay subgrade and uniformly mixing the sand or other admixture raises a serious objection to this method of treatment. It

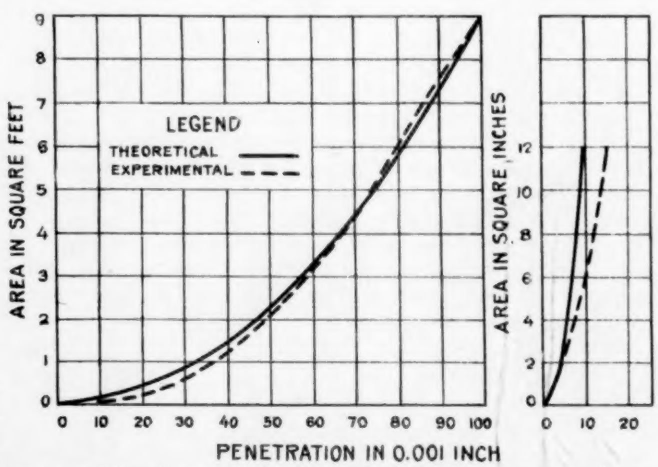

FIG. 7.—Relation of the penetration of the soil to the bearing area of the slab for equal unit loads

would seem therefore that a cheaper method would consist in laying a subbase of sand or gravel or broken stone over the bad subgrades.

Another series of experiments, also by the Bureau of Public Roads, at Arlington has involved the testing of concrete slabs laid on specially prepared subgrades under the simulated impact of a motor truck wheel. Of the six slabs, exactly alike in dimensions and mix, four were laid on subgrades treated with admixtures of Portland cement. Table 2 gives the results of the tests.

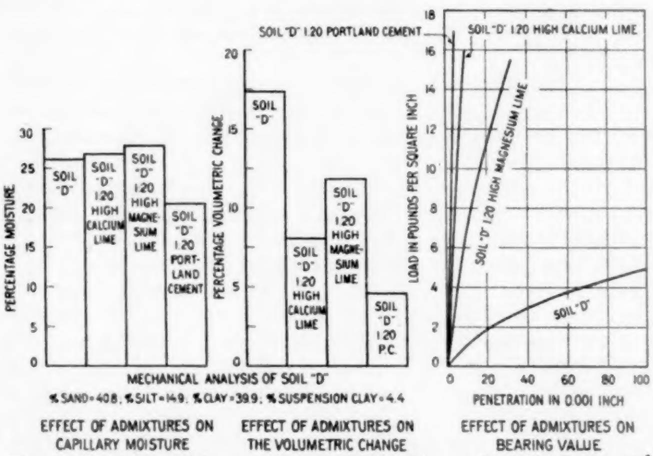

Fig. 8.—Effect of admixtures on the capillary moisture, volumetric change, and bearing value of a subgrade soil

Table 2.—*The resistance to impact of six similar slabs of concrete pavement laid on similar subgrade soils treated in various ways*

Slab No.	Admixture of Portland cement	Height of drop of motor truck wheel	Resistance of slab at failure
		Inches	*Pounds*
1	None	1.34	12,660
2	None	1.09	11,330
3	1 part Portland cement to 14 parts soil	.91	20,650
4	1 part Portland cement to 14 parts soil	.92	19,060
5	1 part Portland cement to 28 parts soil	1.04	18,250
6	1 part Portland cement to 28 parts soil	1.06	18,000

The weight used was equivalent to the load on the rear wheel of a 5-ton truck. The sprung weight was 6,000 pounds and the unsprung 1,980 pounds.

Slabs 1 and 2 were laid on the untreated natural subgrade prepared by excavating to a depth of 1 foot, backfilling in thin layers and tamping. The subgrades under slabs 3, 4, 5, and 6 were dug up in the same way and backfilled after being mixed with the desired proportions of Portland cement. The subgrades under slabs 4 and 6 differ from those under slabs 3 and 5 in that the former were excavated again, reshaped and retamped just prior to the placing of the concrete in order to provide conditions similar to those obtaining in actual construction.

The report of the investigation concludes:

"1. That the admixture of Portland cement with a subgrade soil of low supporting value will result in an improved supporting value.

"2. That relatively greater benefit results from the first few per cent of cement added than from subsequent equal amounts.

"3. That cutting up of this prepared subgrade after it has set up does not materially damage it

"4. Examination of some of this material which had been in place for two years indicates that its physical character is permanently changed. It seems to lose all plasticity and become very firm and granular, even in the presence of excessive amounts of water."

THE PROPER DEPTH OF SUBBASES

The proper depth of subbases under known conditions of subsoil, climate, traffic, and type of pavement is yet to be determined. In a general way tests made by the Bureau of Public Roads indicate that the intensity of pressure on a soft subgrade caused by concentrated loads on the surface decreases as the depth of the surfacing (including the subbase) increases. At this point it may be well to bring out the necessity for detailed tests on sand, crushed rock, or gravel of various sizes and grading used as a subbase under concrete and bituminous pavements to determine the intensity of pressure transmitted to the subgrade by a concentrated load at the surface of the pavement. The study would involve various depths of pavement and subbase and would necessarily be made on the various soil types such as sand, silt, and clay because the intensity of pressure at the subgrade with the same applied load at the surface of the pavement might vary with the elasticity of the soil. The loads would be gradually applied without any impact and later a constant might be determined which, multiplied by the static load, would make allowance for impact. This test in conjunction with similar tests previously mentioned to determine the maximum allowable pressures for various types of subgrade soil, should provide information which would do much to clear up the uncertainty which at present surrounds the subject of pavement design and throw light on the

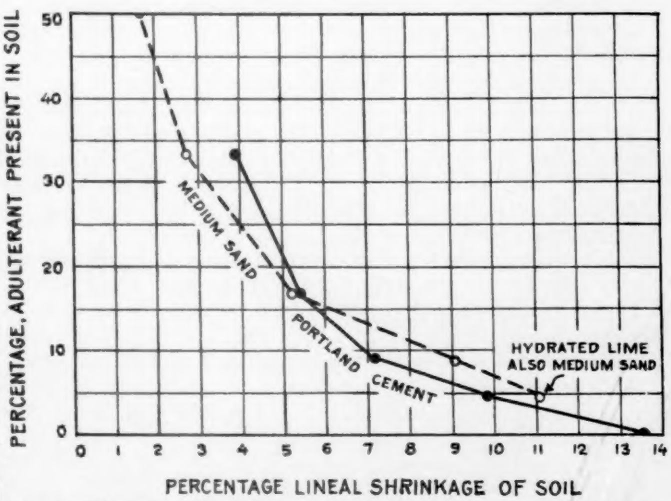

Fig. 9.—Effect of various admixtures upon the shrinkage of a sample of cove clay subsoil

proper dimensions of subbase and surfacing to use under known climatic, subgrade, and traffic conditions.

As to the characteristics of the subgrade[16] which indicates a need for the construction of a subbase, the study of the Columbia Pike experimental road constructed near Arlington, Va., by the Bureau of Public Roads, has led to the conclusion that "subgrades that show as much as 10 per cent volume change, by laboratory test on an entire sample including coarse mate-

[16] Reinforcing and the subgrade as factors in the design of concrete pavements, by J. T. Pauls, Public Roads, vol. 5, No. 8, October, 1924.

rial should be covered with a layer of coarse granular material, and a pavement laid on a subgrade of this character should have a longitudinal joint at the center." The results of the laboratory tests for volume change in this case were corrected to represent the volume change which would have occurred with coarse material present and the sample wetted to capillary saturation. The limits determined in the Pacific Northwest [37] of 14 per cent volumetric shrinkage and 5 per cent lineal shrinkage were established without coarse material and at a moisture content equal to the moisture equivalent percentage. As nearly as can be estimated the upper limit of 10 per cent volumetric shrinkage with coarse material included corresponds to a volumetric shrinkage of from 17.4 to 26.3 per cent as found in the Pacific Northwest. Using the lower figure in order to be conservative, the comparison of the data from the two investigations follows:

	Limiting shrinkage determined in Columbia Pike experiments	Limiting shrinkage determined in the Pacific Northwest
	Per cent	*Per cent*
Volumetric	17.4	14
Lineal	6.3	5

RIO VISTA, CALIF., TESTS ON SUBGRADE ADMIXTURES

In connection with field tests made by incorporating admixtures in the subgrade soil to reduce the volumetric change with variations in moisture content, probably the most recent record of results is that made by C. L. McKesson, materials and research engineer of the California Highway Commission, who has given a great deal of study to the subject of subgrades. Mr. McKesson was in charge of the field subgrade soil tests made by the Bureau of Public Roads in the Pacific Northwest. Excerpts from a memorandum of his made on October 18, 1924, and a large portion of which has never been published before are given here.[38]

"In November, 1921, experimental subgrade treatment was begun on the Rio Vista lateral between Denverton and Rio Vista.

"The treatment consisted of loosening and pulverizing the soil to a depth of 6 and 12 inches, after which various adulterants were mixed with the pulverized soil.

"Eleven 500-foot sections and one 380-foot section were treated as follows:

"Section 1. Station 177+50 to 182+50, 1 to 10, cement mixture, 12-inch depth.

"Section 2. Station 182+50 to 187+50, 1 to 20, cement mixture, 12-inch depth.

"Section 3. Station 194+00 to 199+00, 1 to 10, cement mixture, 6-inch depth.

"Section 4. Station 212+00 to 217+00, 1 to 20, cement mixture, 6-inch depth.

"Section 5. Station 217+00 to 222+00, 1 to 20, hydrated lime, 12-inch depth.

"Section a. Station 248+50 to 253+50, 1 to 10, cement mixture, 6-inch depth.

"Section b. Station 253+50 to 258+50, 1 to 20, cement mixture, 6-inch depth.

"Section c. Station 258+50 to 263+50, 1 to 10, cement mixture, 12-inch depth.

"Section d. Station 263+50 to 267+50, 1 to 20, cement mixture, 12-inch depth.

"Section 6. Station 268+00 to 273+00, 1 to 20, limestone dust, 12-inch depth.

"Section 7. Station 273+00 to 278+00, no foreign substance.

"Section 8. Station 278+00 to 283+00, 60 per cent asphaltic oil, 12-inch depth.

"A detailed description of methods used in preparation of the various sections is to be found in the biennial report of the highway commission 1921–22, pages 61 to 64. * * *

"The subsoil on sections a, b, c, and d was treated in November, 1921, and the remainder in the summer of 1922. Pavement was constructed in the summer of 1922.

"The subsoil under the various sections is adobe and silty clay soil. There is no record in the laboratory of any analyses of the soil having been made or of any laboratory experimental work in connection with this test. In the description of the work it is stated that 'it was necessary to select segregated sections as there was no stretch of road which would permit of continuous section.' It is reasonable to assume, therefore, that an effort was made to select sections where subsoil conditions were as nearly identical as it was possible to secure. There is, however, a considerable variation in the quality of the subsoil on the various sections chosen. * * *

"A 4-inch gravel sub-base was placed on all heavy soil subgrade on the project except on the experimental sections and it is therefore possible to compare this more or less standard method of subgrade treatment with the various admixture treatments.

"The attached prints (fig. 10) show the condition of the pavement, station 240 to 285, on April 2, 1924, and station 172+50 to 227+00, on September 15, 1924.

"The relative efficiency of the various methods of treatment based on the present condition of the pavement is as follows:

"*Four-inch gravel subbase on untreated subsoil* is found to be very efficient. All sections in good condition. No longitudinal cracks and transverse cracks are 40 to 100 feet apart.

"*Six-inch Portland cement (secs. a, b, 3, and 4).*—Where subsoil is similar there is little or no difference apparent between sections having 1:10 and 1:20 admixtures. Failures consist of transverse cracks averaging 40 feet apart.

"*Twelve-inch asphaltic oil (5 gallons per square yard, sec. 8).*—This section has transverse cracks averaging 25 feet apart. There is little difference in condition between this section and the 12-inch Portland cement sections.

"*Twelve-inch hydrated lime (sec. 5).*—This section has transverse cracks 10 to 60 feet apart and several short irregular longitudinal cracks. Some surface checking was also noted.

"*Twelve-inch Portland cement sections.*—Sections 1 and c with 1:10 admixture are in slightly better condition than sections 2 and d having 1:20 admixture. Transverse cracks on average about 25 feet on sections 2 and d. Sections 1 and 2 have a number of longitudinal cracks. The average condition of these sections is slightly better than the plain, untreated section 7 but not enough to justify any expenditure.

[37] Practical tests for subgrade soils, by A. C. Rose, PUBLIC ROADS, vol. 5, No. 6, August, 1924.

[38] See also Fourth Biennial Report of the California Highway Commission, Nov. 1, 1924, p. 77.

"*Plain 12-inch.*—This section was plowed up and soil pulverized as for admixture treatments. It was then rerolled without the addition of any adulterant. Pavement on this section is in a little worse condition than on 12-inch 1:20 cement section but the soil is apparently heavier than an any other section of the experimental work. A comparison of this section with gravel subbase sections shows clearly the benefit to be obtained from the use of a gravel subbase.

"*Twelve-inch limestone dust* (*sec. 6*).—This section is in the worst condition of all. The pavement is broken up into narrow strips by the many transverse cracks and in some places short longitudinal cracks are numerous. Had it not been for transverse reinforcement this section would probably be a total failure.

"When this experimental work was started in 1921, Mr. A. C. Rose, who had for 18 months previously been making soil studies in the United States Bureau of Public Roads district 1 under my immediate supervision, called to my attention the press reports on Solano–53–B. At my suggestion he immediately started a series of tests to determine the probable effect of the proposed adulterants upon what we believed to be the two most important characteristics of a soil, namely, shrinkage and moisture retaining capacity as indicated by its moisture equivalent. In addition to the use of lime, cement and limestone as adulterants, we included specimens adulterated with fine, medium, and coarse sand believing that these adulterants would be found equally efficient. The soil selected for the experiment was Cove clay which corresponds very closely with the soil on Sol.–53–B. It contained 44.9 per cent clay and 40.6 per cent silt against 41.6 per cent clay and 37.2 per cent silt in a typical sample from the Solano project.

"The results of the tests made by Mr. Rose are shown in Table 3.

TABLE 3.—*Showing effect of adulterants on shrinkage of Cove clay subsoil*

Kind of mixture	Moisture equivalent; average of 2 runs	Lineal shrinkage; average of 2 runs	Volumetric shrinkage (computed)
	Per cent	*Per cent*	*Per cent*
1 Portland cement to 2 soil	31.4	3.90	12.8
1 Portland cement to 5 soil	36.7	5.40	15.2
1 Portland cement to 10 soil	42.4	7.20	20.2
1 Portland cement to 20 soil	43.3	9.84	26.8
1 hydrated lime to 20 soil	47.3	11.10	29.8
1 pulverized limestone to 20 soil	41.4	13.82	36.0
1 medium sand to 1 soil [1]	20.1	1.64	5.0
1 medium sand to 2 soil	25.7	2.73	8.0
1 medium sand to 5 soil	35.4	5.30	15.0
1 medium sand to 10 soil	38.1	9.08	24.9
1 medium sand to 20 soil	39.4	11.10	29.9
1 coarse sand to 2 soil [2]	25.9	5.20	15.0
1 fine sand to 2 soil [3]	27.5	7.32	20.5
All soil	40.5	13.46	35.2

[1] Medium sand: Passing 10 mesh and retained on 20 mesh, 33 per cent; passing 20 mesh and retained on 40 mesh, 67 per cent.
[2] Coarse sand: Passing ¼ inch and retained on 10 mesh, 33 per cent; passing 20 mesh and retained on 40 mesh, 67 per cent.
[3] Fine sand: Passing 40 mesh and retained on 200 mesh, 100 per cent.

"The results were summed up as follows:

"1. Portland cement and ordinary sand of medium coarseness were found to be *equally effective* in lowering the moisture equivalent and shrinkage factors of a soil. A 1 to 10 or 1 to 20 mixture of either cement or sand with clay soil was found to reduce the shrinkage factor only a few points and the soil after such treatment was not suitable for use in subgrade for pavement. Such admixtures were therefore reported to be useless. In order to lower shrinkage to a point of approximate safety (5 per cent lineal shrinkage) it was found necessary to use one part of cement to two parts of soil. Such a treatment would of course be extremely costly. Sand used in the same proportion (1 to 2) changed the soil from a clay to a clay loam and reduced the shrinkage somewhat more than did the Portland cement.

"2. Hydrated lime in 1 to 20 proportion was found to be practically useless, the lineal shrinkage being reduced only 2 per cent (13 to 11 per cent).

"3. Pulverized limestone was found to be positively detrimental in that it increased both shrinkage and moisture equivalent.

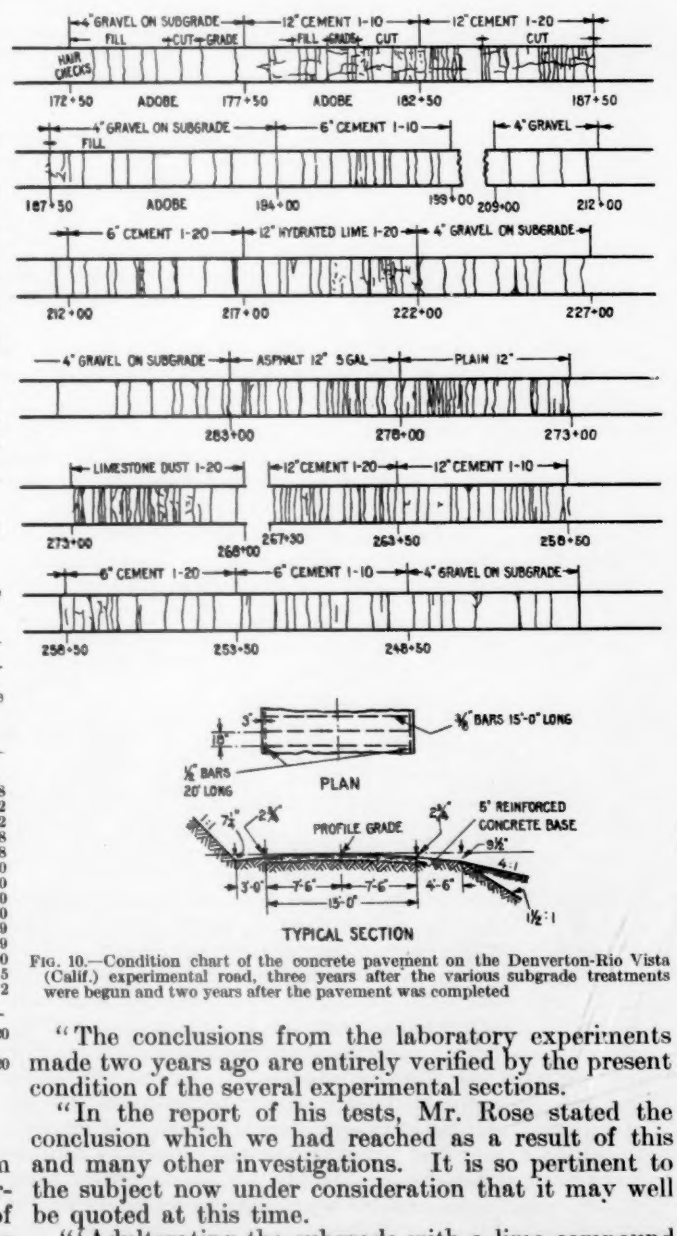

FIG. 10.—Condition chart of the concrete pavement on the Denverton-Rio Vista (Calif.) experimental road, three years after the various subgrade treatments were begun and two years after the pavement was completed

"The conclusions from the laboratory experiments made two years ago are entirely verified by the present condition of the several experimental sections.

"In the report of his tests, Mr. Rose stated the conclusion which we had reached as a result of this and many other investigations. It is so pertinent to the subject now under consideration that it may well be quoted at this time.

"'Adulterating the subgrade with a lime compound or sand to a depth of 1 foot reduces shrinkage in the portion adulterated, but the subsoil for a considerable depth beneath this treated layer would continue to swell and shrink and displacement of the upper layer

and of the pavement would doubtless continue although to a less degree. The efficiency of this method of subgrade treatment is doubted. It is believed that a better treatment of heavy soil subgrade is:

"'1. To use a sand cushion to act as an equilibrant to run into irregularities of the subgrade which is deformed by shrinkage or swell of the soil and thus to maintain a uniform surface in contact with the base of the pavement,[39] or

"'2. To establish an unchanging moisture content in the immediate subgrade.'

"The mixed sand and gravel treatment and a special side ditch design was adopted in 1921 on a 4-mile stretch of pavement [40] constructed on this same Cove clay and this spring after two and one-half years the pavement without reinforcement was entirely free from longitudinal cracks and transverse cracks were infrequent. (Expansion joints were used at 30-foot intervals.)

"The results of the Rio Vista lateral experiment appear to justify three conclusions:

"1. That the soil adulteration with cement or lime compounds is not an efficient or economical method of securing stability in heavy soils.

"2. That the suitability of the soil for subgrade purposes, or the merits of various methods of soil treatment can be determined by relatively simple laboratory tests and that expensive field tests can, in some cases at least, be avoided by first resorting to a properly conducted laboratory investigation.

"3. That a sand or gravel layer is an efficient and economical method of minimizing damage to pavement resulting from swelling or shrinkage of the subsoil."

The costs per lineal foot of roadway for each of the methods of treatment as shown by the cost records of Mr. McKesson follow:

Section No.	Treatment of subgrade		Cost per lineal foot
1	1 to 10 cement mixture	12-inch depth	$2.20
2	1 to 20 cement mixture	do	1.275
3	1 to 10 cement mixture	6-inch depth	1.265
4	1 to 20 cement mixture	do	.752
5	1 to 20 hydrated lime mixture	12-inch depth	.921
6	1 to 20 limestone dust mixture	do	.817
7	No foreign substance		.189
8	60 per cent asphaltic oil	12-inch depth	.957

The cost of the 4-inch gravel sub-base is not available but Mr. McKesson estimates this at $4 per cubic yard in place or $0.74 per lineal foot of pavement.

It should be remembered, however, that these Rio Vista experiments were carried on under unique conditions. The adobe soil and the hot, desiccating winds provided a dry, parched subgrade which made it essential to wet the soil thoroughly before the pavement was laid. If there was any difference in the amount of wetting of the various sections, it is possible that the amount of cracking of the pavement might have been affected considerably. It is also interesting to compare these results with the experiments of the Bureau of Public Roads at the Arlington Farm. On the Columbia Pike Road the section of subgrade treated with Portland cement in the proportion of 1 part of cement to 28 parts of soil to a depth of 6 inches, showed up remarkably well. This section had no longitudinal cracks as compared with the two adjacent untreated sections, where the pavement had cracked badly. The soil was a clay. Other experiments of the Bureau of Public Roads which are described elsewhere in this article indicate that the bearing power of a subgrade soil is materially increased by the addition of Portland cement as an admixture. It would seem, therefore, that the results of all these experiments with admixtures are inconclusive. Sufficient work has not been done to determine the practicability or impracticability of using Portland cement or hydrated lime to improve the quality of subgrade soils.

S MIGRAVEL, TOPSOIL, AND SAND-CLAY ROADS

Dr. C. M. Strahan, who has made a comprehensive study of semigravel, topsoil and sand-clay roads,[41] states that: "The excellent topsoils are most largely found on the ridges of northeast Georgia where they lie in many deposits weathered in place from limited outcrops of porphyritic granites and coarse-grained sandstones. Here also many of the semigravel types are found consisting of partially decomposed granite soils. Other semigravels are found along the margin of an old geologic sea beach which enters the State on the east in Lincoln County and swings in a wide southwesterly arc to the Alabama line." And further on in the bulletin he states: "Southwest Georgia, notably adjoining the Flint River, abounds in sand-clay soils derived from Cretacious rocks and carrying from 5 to 25 per cent of a nodular iron-silica gravel. These deposits are liberally distributed and from them have been built a large mileage of remarkably efficient roads." These roads, as described by the Georgia bulletin, provide a low-grade but efficient and inexpensive surfacing material.

From an investigation of the condition of existing roads under different classes of traffic the author has evaluated the extreme limits by percentages of the coarse material, sand, silt, and clay for the three types of surfacing called class A (hard), class B (medium), and class C (soft). It is evident from an examination of these data that the methods outlined could be used elsewhere in the country as well as in the Southern States. It is also evident that the same low-grade types of surfacing are used elsewhere although they are not known by the same name, but the thorough study of the qualities of the material given by the University of Georgia has not been made elsewhere. For example in central Oregon, near the town of Burns, suitable standard gravel surfacing was not found for a Federal-aid project. This road extended over an old geological lake bed with coarse sand and pea gravel within three feet of the surface soil which was composed of volcanic ash. The latter was stripped from the semigravel deposit which was used to build an excellent surfacing for the moderate traffic on the project. Undoubtedly there are innumerable instances where the same treatments could be and have been used in other sections of the country.

[39] It has been suggested that besides the vertical distortion of the subgrade due to shrinkage there are tensile stresses developed by the horizontal shrinkage of the soil. There is adhesion between the base of the pavement and the subgrade. It is possible that the granular layer destroys this adhesion by providing a sliding plane, which prevents high stresses being developed in the pavement due to the horizontal shrinkage of the subgrade soil.

[40] Oregon Federal-aid project No. 51.

[41] Research work on semigravel, topsoil and sand-clay, and other road materials in Georgia, Bulletin of the University of Georgia, vol. 22, No. 59, Serial No. 326, June 1922.

Sand-clay and semigravel roads studied, PUBLIC ROADS, vol. 5, No. 8, October 1924 p. 16.

The Georgia bulletin calls attention to the fact that, "Knowing the variable supporting power of ordinary soils under wet conditions, if selected road soils applied to the graded road bed can give them a uniform stability such soils offer a valuable treatment of the subgrade preceding the laying of pavements." [42] This is unquestionably true. On the other hand there is a possibility that the graded classification of topsoil, sand-clay, and semigravel surfacing material may be interpreted by some as a logical general method of differentiating between existing good and bad subgrade soils although Doctor Strahan has never advanced such an interpretation. The area shown on the trilinear chart in Figure 11 represents the extreme limits of the sand-clay, topsoil and semigravel classification. The clay fraction has been divided by two and included with the silt to make a comparison with the soil grain sizes of the Bureau of Soils. It will be observed that the area is only a small portion of the sand and sandy-loam classification of the Bureau of Soils. The coarse material present in the topsoil or similar material is not represented in the trilinear chart and need not be considered because of its obviously beneficial nature. It seems evident, therefore, that there are large areas of sand, sandy loams, loams and silt-loams which would make good subgrade material without treatment, but which are not included within the limits adopted for sand-clay, topsoil and semigravel roads. The classification would, therefore, seem to be of very restricted value for evaluating good and bad subgrades.

CAPILLARY MOISTURE AND ITS EFFECT ON SUBGRADE SOILS

During the past few years considerable attention has been given to the effect of capillary moisture upon the stability of highway subgrades. Free water is commonly distinguished from capillary water as the water in the soil which is not held by capillarity and obeys the laws of gravity. But tests conducted recently by the division of agricultural engineering of the Bureau of Public Roads tend to qualify this generally accepted definition differentiating between capillary and free water on the basis of gravity. The report of the tests, as published in a bulletin of the Department of Agriculture,[43] states: "From these data and as a result of tests by the writer and others, it can be said that a vertical soil column can take up by capillarity from a body of free water more water than it can hold against gravity, if the free water be removed from the bottom of the soil column; that is, if the vertical tube is filled with soil and the lower end placed in a vessel of water and allowed to stand for a month or longer and the water is then removed from the tank, a part of the moisture in the soil column will drain out. To repeat—a vertical soil column will take up by capillarity from a body of water more moisture than it can retain when the source of the water is removed." It would appear that the amount of capillary water in a subgrade where the source of the moisture is a wet soil would be less than when the source is a body of free water. The capillary moisture in a soil might, therefore, be reduced by lowering the ground water table considerably where it is not possible to eliminate it altogether. Often, however, it is neither possible nor practicable to lower or eliminate the ground water table.

[42] Research work on semigravel, topsoil and sand-clay, and other road materials in Georgia, Bulletin of the University of Georgia, vol. 22, No. 59, Serial No. 326, June, 1922, p. 5.

[43] Capillary movement of soil moisture, by W. W. McLaughlin, U. S. Dept. of Agric. Bul. No. 835, p. 62.

As a result of the subgrade drainage experiments conducted by the Bureau of Public Roads at the Arlington Experimental Farm, "it is concluded that systems of drainage merely remove the free water in the subgrade, but can not remove capillary moisture. * * *." [44]

Charles M. Upham, director of the highway research board, and H. F. Janda, the assistant director, conclude: [45]

"1. That drain tile are of no direct value in removing or preventing the rise of purely capillary moisture.

"2. That the percentage of capillary moisture is reduced as the elevation of the subgrade above the water table is increased. Therefore, a tile drain might reduce the percentage of capillary moisture by lowering the water table."

Some interesting comments on the relation of capillary water to highway subgrades were made as early as 1921, by an irrigation engineer of the Bureau of Public Roads.[46]

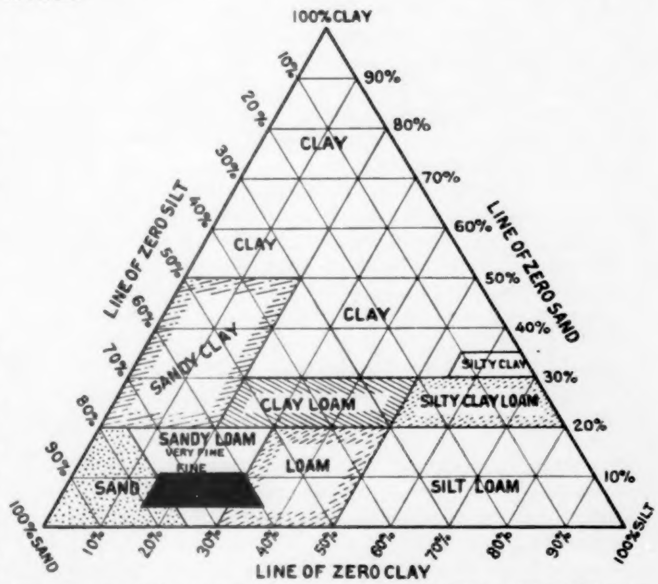

FIG. 11.—The black area represents the approximate limits of the sand-clay surfacing and also of the sand, silt, and clay fractions of the topsoil and semigravel classification

The concensus of opinion seems to be that it is not possible to remove capillary water from highway subgrades. Only the free water may be removed by practical methods.

EXPERIMENTS WITH ADMIXTURES FOR THE IMPROVEMENT OF EARTH ROADS

A number of experiments have been carried on recently by the Bureau of Public Roads and other agencies to determine whether the wearing qualities of earth roads may be improved by the addition to the soil of such admixtures as lime and Portland cement. None of the experiments has thus far developed information of direct value for the solution of the subgrade problem, a fact which is not surprising in view of the different purposes of the admixture in the two cases. In the first case the objects of admixture are to reduce the plasticity and increase the bearing power

[44] Researches on the structural design of highways by the United States Bureau of Public Roads, by A. T. Goldbeck, Transactions of the Am. Soc. of Civil Eng., vol. 88, p. 264, 1925.

[45] Removal of capillary moisture in highway subgrades, by Charles M. Upham and H. F. Janda, Engineering News-Record, col. 93, No. 23, Dec. 4, 1924, p. 912.

[46] Capillary moisture and its effect on highway subgrades, by W. W. McLaughlin, PUBLIC ROADS, vol. 4, No. 1, May, 1921, p. 6.

of the exposed surface soil and so make it less susceptible to rutting and capable of being used as a wearing surface throughout a greater portion of the year than would otherwise be possible. For this purpose the curative is mixed to comparatively shallow depths; and the plasticity of the surface is further reduced by unrestricted evaporation. In contrast to this, the admixtures used to improve the stability of a subgrade under a pavement must not only reduce the plasticity and thus increase the bearing power but they must also eliminate or minimize the volume changes of the soil with variations in moisture content or freezing. This volume change affects the soil to a considerable depth—at least a foot and probably more. In addition, the evaporation is restricted in this case by the pavement and condensation may occur. It would seem, therefore, inadvisable at this time to forecast beneficial or adverse results of subgrade admixture based upon the information at hand in regard to the effect of admixtures on earth wearing surfaces, or vice versa. However, the two problems are not totally dissimilar, and it may be well to record briefly the principal developments of the surface investigations, if for no other reason than the possibility that they may suggest to some one a new approach to a solution of the subgrade problem.

The first of the field experiments of the Bureau of Public Roads, made in cooperation with the State Highway Department of Iowa, was built north of Chariton in Lucas County during the summer of 1924. The road consisted of 17 sections 400 feet long, treated with proportions of hydrated lime and Portland cement varying from 3 to 9 per cent. The engineer [47] in charge of the tests for the bureau reports, with respect to the effect of the treatment, as follows: "On September 1 (1924) we had the opportunity of studying the effect of the cement-treated sections. It was found that all colloidal properties had been destroyed. No plasticity whatever remained and in consequence of this fact the treated section showed no disposition whatever to make mud. To all intents and purposes it was as firm and mudless as any pavement, lacking only the characteristic firmness of the concrete slab. Even after we had cut into the surface a considerable distance no tendency whatever was manifested to stick as is the case in ordinary untreated gumbo when wet.

"One thing is certain, the cement does destroy colloidal conditions but whether or not a road so constructed will prove dustless is a matter for time to disclose."

On December 11, 1924, W. O. Price, of the Iowa State Highway Department, made an inspection of the project after a freezing spell to determine if there were any truth in the local reports that the experimental road was a failure. His report states: "On the experimental road we found several places where ruts had been cut down 4 or 5 inches deep with intermediate ridges. This was especially noticeable on the south two sections of the lime treatment, which are 3 and 5 per cent, and also on some of the other 3 per cent pieces. It was noticeable, however, that the frozen part was not so hard. It was either dryer and consequently had not frozen so hard or else it had thawed more rapidly. On practically all of the other sections even though they appeared rough on the surface one could drive a car at most any place without noticing the rough condition of the road, the surface of which was considerably dryer than the untreated sections. I believe that they could readily have been dragged at that time or perhaps an hour or two later in the afternoon whereas nothing could have been accomplished on the untreated road in that direction except possibly at some places along the edge where traffic had not gone while they were muddy. * * *

"To sum up, it appears that the treatment permits the working of the road earlier after a rain than the untreated road."

Another of the bureau cooperative experiments with the State of Iowa was near Glenwood in Mills County. The project consisted of 9 sections, each 1,000 feet in length and treated with 3, 5, 7, and 9 per cent of hydrated lime and Portland cement. The depth of the admixture was 6 inches. The project was built during September, 1924. On January 22, 1925, a Bureau of Public Roads engineer [48] reported:

"On the date of this inspection the ground was frozen to a considerable depth. The day was warm and the surface of the roadway had thawed to a depth of about 1 inch. The earth road where no treatment had been made was rutted, rough and quite slippery. It was quite difficult to turn a car out of the ruts.

"The difference in the condition of the 3 per cent road and the ordinary earth road was not noticeable. A marked improvement was quite noticeable on the remainder of the project. A considerable portion was fairly dry and but slightly rutted. A few places were somewhat slippery especially where the road surface was not fully exposed to the sun and wind. At this time there appeared to be no appreciable difference between the cement and lime treatments * * *.

"It is quite evident that a beneficial effect has been produced by the admixture treatment of cement and lime on the 5, 7, and 9 per cent sections especially during the winter months. Just how long * * * this treatment will be effective is quite problematical * * *."

The cooperative project, in which the bureau joined with the State Highway Department of South Dakota, was located on a road near Fort Pierre, S. Dak. The gumbo surface was treated in October, 1924. There was practically no rainfall during the following winter and on May 21, 1925, the bureau's inspecting engineer [49] reported as follows: "I found the several sections to be in substantially the same condition as untreated gumbo. The surface of all sections appeared to be substantially pure gumbo for about 1 inch in depth and below this was a mixture of more or less finely divided gumbo with cement or lime. The cement or lime is still in a dry powdered state and does not appear to have received any moisture since it was placed on the road."

Other experiments, practically completed by the bureau, at the Arlington Experimental Farm, indicate that hydrated lime and Portland cement admixtures will improve the wearing surface of earth roads. At least the results found to date are promising. Whether the cost of the treatment will be of sufficient value to warrant the expenditure or whether the beneficial results are lasting will require more extended observations. It is too early yet to formulate any definite conclusions.

[47] W. L. Spoon, senior highway engineer.

[48] C. H. Semper, associate highway engineer.

[49] A. I. Ostrander, highway engineer.

THE MISSOURI EXPERIMENTS

The engineering experiment station of the University of Missouri has recently conducted a series of tests similar to those reported above.

With regard to these tests, Prof. E. J. McCaustland writes as follows:[50]

"At a somewhat later time selected stretches of clay roads, subject to heavy traffic, were treated with varying percentages of hydrated lime and these stretches have been kept under observation for a number of months. The winter season of 1924–25 was an extremely trying one on these test roads because of a heavy fall of sleet and ice early in December and a continuation through the winter of alternating periods of thawing and freezing. In every case, however, these test sections, all of which have been carrying traffic during the past 7 to 11 months, show to the most casual observer the distinct advantage of lime admixtures in preventing surface stickiness and the formation of deep ruts under traffic. In brief, it seems to have been established beyond question that the addition of hydrated lime in the proportion of 2 to 5 per cent dry weight to clay soils will materially reduce the tendency to form mud and prevent to a great degree the formation of ruts; there is reason to believe, however, that such treatment will not in any degree lessen the production of dust and in some cases the dust may be increased." The writer continues by pointing out that the maintenance costs are considerably reduced by the lime treatment since workers are able to begin work when the road is soft and workable immediately after a rain. There also appears to be no marked difference in the results caused by incorporating the admixture to different depths, and this is considered of importance since it affects the cost of treatment.

Professor McCaustland goes on to say that only negative results have been found in trying to determine the basic physical phenomena which are brought about by the lime admixture, and adds: "These facts are apparently established, however. The specific gravity of the soil is only slightly reduced by adding hydrated lime, the moisture holding capacity and moisture equivalent are reduced in heavy clays: The rate of evaporation is slightly retarded; but there is a more rapid capillary movement of the moisture after treatment; the voids in the soil became enlarged allowing an increased rate of percolation; and the bearing power at the higher moisture content is increased. We can not, however, at this time offer a scientific explanation of these phenomena."

The results of these experiments are interesting in so far as they suggest the possibility of improving the all-year condition of a large mileage of low-type roads throughout the country. It should be remembered, however, that the experiments are not conclusive of the ultimate benefit to be obtained by lime admixtures because of the short time during which the tests have been made—less than a year. It is possible that the further lime treatments made necessary by traffic may make the cure more serious than the disease because of the irritation of the nose, throat, and eyes by the lime dust during the dry seasons of the year. This is suggested as a possibility by Professor McCaustland when he writes: "Such treatment will not in any degree lessen the production of dust and in some cases the dust may be increased." The investigations are worthy contributions to professional literature although it is believed that final judgment as to the ultimate value of the lime admixture for improving the all-weather qualities of winter roads should be withheld pending further observations over a period of years or accelerated tests which shall take into consideration seasonal changes and additional treatments.

[50] Dirt roads improved by lime mixed with surface soil, by E. J. McCaustland, dean, School of Engineering, University of Missouri. Extract from paper read before National Lime Association at Briarcliff Manor, New York, May 26-29, 1925, Engineering News-Record, vol. 94, No. 26, June 25, 1925.

CONCLUSIONS

Relating to subgrade studies completed or in progress.—

1. Generally speaking, all the data obtained in the United States indicate, the character of the clay remaining constant, that good subgrade soils have a low clay content by mechanical analysis and bad subgrade soils are characterized by a high percentage of clay. An illustration of an exception is the "rotten limestone" formation in the Black Waxy Belt of Texas, which, though high in clay is not a bad subgrade material. Pending further investigations, this finding should be accepted with reservations in this country and should not be applied to the soils of foreign countries without a thorough check against local conditions because there are well-known exceptions. An example of the latter are certain soils of the humid, tropical sections of Central and South America. With as much as 90 per cent of clay by mechanical analysis these soils are porous and not sticky. This is believed to be due to the oxidation of the colloids throughout the centuries in the warm, wet climate.

2. In general, the laboratory tests by the Bureau of Public Roads show that soils with a high percentage of clay have a high moisture equivalent percentage, a high capillary moisture capacity, a high volumetric shrinkage percentage, a low comparative bearing value, a high dye adsorption percentage, and require a long time for slaking.

3. Field methods for identifying good and bad subgrade soils have been devised by the Bureau of Public Roads. These involve the use of Bureau of Soils bulletins to locate the soil types and field tests for determining the moisture equivalent and lineal shrinkage percentages in order to evaluate the character of the subgrade soil.

4. The construction methods which may be adopted in bad subgrades, assuming the quality of the materials and the workmanship on the pavement to be uniform, are in general as follows:

(*a*) Use upland coarse grained soils for building fills over lowland clay soils.

(*b*) Use side ditches of special design.

(*c*) Use tile drains. In heavy clays these are generally useless except in uncommon cases such as open seams or pores in the soil, water-bearing strata, or hydrostatic pressure.

(*d*) Use a granular subbase such as sand, sand-clay, topsoil, stone, or gravel.

(*e*) Thicken the pavement.

(*f*) Add steel reinforcement.

5. The study of the California highway system by the Bureau of Public Roads showed that 70 per cent of the pavement failures occurred on adobe soils. The cracking of the pavements on adobe soils indicated a distortion of the subgrade due to varying moisture content and shrinkage.

6. The laboratory studies of the Bureau of Public Roads indicate that the moisture equivalent percentage of a subgrade soil is a critical percentage with respect

to the bearing power of the soil. This does not mean that soils with a moisture content in excess of the moisture equivalent percentage will not support reasonable loads but that beyond the moisture equivalent percentage the bearing power of the soil falls off rapidly.

7. The field experiments of the Bureau of Public Roads in the Pacific Northwest indicate that a lineal shrinkage percentage of 5 per cent is, for that region, the maximum for a good subgrade soil. The Columbia Pike experiments of the bureau roughly checked this figure. The limit in the latter case was approximately 6 per cent.

8. Defining the term "stability ratio" as the actual moisture content percentage of the soil divided by its moisture equivalent percentage, the field investigations of the Bureau of Public Roads in the Pacific Northwest indicate that the bearing power of a soil is relatively low when the stability ratio is greater than unity. This does not apply to frozen soils. The bearing power of the soil by laboratory tests is relatively low also when the "moisture index" is greater than unity.

9. Clay soils, as compared with sands, show a relatively large heave when frozen according to field tests by Stephen Taber, State geologist of South Carolina.

10. Bureau of Public Roads laboratory tests show a greater percentage of water freezable in sands than in clays. This does not mean that the amount of the heave in sands due to freezing will be greater than in clays. On the contrary, it would seem that the greater heaving would occur in clay with capillary water present because of the greater total amount of water frozen.

11. In climates where freezing occurs, field observations indicate that for concrete pavement slabs of 60 feet or less in length:

(*a*) Cracks are infrequent in pavement laid on well-drained sand or porous subgrades.

(*b*) The more compact the subgrade soil, the more frequently cracks occur.

12. The permeability of soils or the porosity seems to increase with the size of the soil grains, the character of the grains remaining constant.

13. The best subgrades are found in fills and the worst in cuts.

14. The selection and redistribution of subgrade soils to secure a stable roadbed is a possible method of construction. The use of a granular subbase over the undisturbed subgrade soil is the more general practice.

15. A sand subbase prevents clay subgrade material from working up into the voids of a macadam road.

16. The Pittsburg and Bates Road soil findings indicate that the character of a subgrade soil may be improved by physical or mechanical processes.

17. The investigations of the Bureau of Public Roads indicate that the bearing value of a soil, for a given penetration of the bearing area, depends on the magnitude of the area. When small bearing areas are used, the intensity of pressure required to produce a penetration of 0.1 inch far exceeds that for large-sized blocks.

18. Sufficient work has not been done up to this time to determine the practicability or impracticability of using admixtures such as Portland cement or hydrated lime to improve the quality of subgrade soils.

19. Granular subbases seem to be more beneficial on bad subgrades than admixtures of Portland cement or hydrated lime.

20. Sand is as effective as Portland cement or hydrated lime when used as an adulterant to reduce the shrinkage of a clay soil.

21. Semigravel, topsoil, and sand-clay roads provide effective surfacing material in the Southeastern States. They could be and have been used elsewhere but under other names.

22. The hair cracks occurring during the curing period of concrete pavements laid on the loess soil of western Iowa were eliminated practically by a layer of tar paper on the subgrade.

23. Investigations made by the Bureau of Public Roads indicate that it may be possible to control the maximum moisture content of a subgrade to approximately the moisture equivalent percentage. Further studies are needed to confirm or disprove this.

24. It is not possible to remove capillary water from subgrades by drainage. Free water only may be removed by practical methods.

Relating to future subgrade soil studies.—Subgrade studies [51] which seem to be immediately necessary to accelerate the progress of subgrade soil investigations should involve probably not only the internal characteristics of different subgrade soils under varying physical and chemical conditions, but also the limiting external forces which may be applied to the subgrade soils under given conditions.

The specific studies which seem to be required immediately are:

1. A classification of soils by series and type names to conform as nearly as possible with the nomenclature and grading used by the United States Bureau of Soils in its soil survey bulletins.

2. The development of simple and decisive laboratory and field tests for subgrade soils.

3. The determination of the distribution of pressure to subgrades of various types through pavements and subbases of varying thicknesses and kind.

4. The determination of the maximum pressure per unit of area permissible, with various types and thicknesses of pavements and subbases, for different soil types with varying percentages of sand, silt, and clay.

5. The determination of the maximum moisture content of well-drained soils, by types and regions, throughout the year, and the maximum moisture content below which it is possible to control the water content of soils by types and regions.

6. The determination of the characteristics of soils, by types and regions, which make one more plastic than another and subject to a greater volume change with variations in moisture content, etc. If found that the active part of a soil is rendered inert over long periods of time by natural physical and chemical phenomena, investigations should follow to determine if similar results may be accomplished by accelerated artificial processes.

7. The determination of the maximum allowable shrinkage limits of soils wetted with comparable amounts of water (such as the moisture equivalent or capillary percentages) by soil types and regions. This would involve condition studies of existing pavements.

[51] Digest of problems in the structural design of highways suggested by contact men in the various State highway departments, Proceedings of the Fourth Annual Meeting of the Highway Research Board, Division of Engineering and Industrial Research, National Research Council, 1925, p. 66.

8. The determination of the mechanical analysis, moisture equivalent and other test limits of those soils with varying degrees of permeability such that tile drains are either unnecessary, effectual, or worthless.

9. The discovery of the stages which accompany the phenomena of freezing of soils under existing pavements:

(*a*) Under continuous freezing conditions.

(*b*) Under conditions of alternate freezing and thawing.

BIBLIOGRAPHY

PUBLIC ROADS.

Soil conditions make situation in Nevada difficult, by C. C. Cottrell, vol. 1, No. 3, July, 1918.
Drainage increasingly vital with growth in heavy traffic, by E. W. James, vol. 1, No. 3, July, 1918.
Native mixed sand-clay for Alabama Federal road, by J. T. Bullen, vol. 1, No. 4, August, 1918.
Maintaining earth roads with oil, by Thos. H. MacDonald, vol. 1, No. 5, September, 1918.
Maintenance of sand-clay roads, by George A. Duren, vol. 1, No. 9, January, 1919.
Calcium chloride as a dust preventive, by W. Leroy Ulrich, vol. 1, No. 11, March, 1919.
Sand-clay from salt flats for surfacing Texas roads, by R. H. Phillips, vol. 1, No. 11, March, 1919.
Water and the subgrade, by J. L. Harrison, vol. 1, No. 12, April, 1919.
Subgrade investigations begun by Bureau of Public Roads, vol. 2, No. 24, April, 1920.
Valuable study of movement of capillary water in soil, vol. 3, No. 28, August, 1920.
The study and treatment of the different subgrades and foundations, by Chas. M. Upham, vol. 3, No. 33, January, 1921.
Outstanding features of report of California highway study, vol. 3, No. 36, April, 1921.
Capillary moisture and its effect on highway subgrades, by W. W. McLaughlin, vol. 4, No. 1, May, 1921.
Tests for subgrade soils, by A. T. Goldbeck and F. H. Jackson, vol. 4, No. 3, July, 1921.
Preliminary report on the Bates experimental road, by Clifford Older and H. F. Clemmer, vol. 4, No. 5, September, 1921.
The field of highway research, by W. K. Hatt, vol. 4, No. 5, September, 1921.
Subgrade drainage tests yield interesting preliminary data, by Ira B. Mullis, vol. 4, No. 6, October, 1921.
Road material tests and inspection news, Subgrade studies, vol. 5, No. 1, March, 1924.
Practical field tests for subgrade soils, by A. C. Rose, vol. 5, No. 6, August, 1924.
Road material tests and inspection news, Field investigation of subgrade soils, vol. 5, No. 7, September, 1924.
Reinforcing and the subgrade as factors in the design of concrete pavements, by J. T. Pauls, vol. 5, No. 8, October, 1924.
Road material tests and inspection news, Sieve limits for the mechanical analysis of subgrade soils, vol. 5, No. 8, October, 1924.
The supporting value of soil as influenced by the bearing area, by A. T. Goldbeck and M. J. Bussard, vol. 5, No. 11, January, 1925.
Percentage of water freezable in soils, by A. M. Wintermyer, vol. 5, No. 12, February, 1925.
Vertical pressure of earth fills measured, by C. W. Connor, vol. 6, No. 1, March, 1925.
Procedure for testing subgrade soils, by J. R. Boyd, vol. 6, No. 2, April, 1925.
Condition of the Ohio post road after 10 years under traffic, by F. H. Jackson, vol. 6, No. 4, June, 1925.
Field methods used in subgrade surveys, by A. C. Rose, vol. 6, No. 5, July, 1925.

Miscellaneous publications:
Report of a study of the California highway system by the United States Bureau of Public Roads to the California Highway Commission and highway engineer. Issued 1920. Revised 1921. Government Printing Office, 1922.
Report of highway research at Pittsburgh, Calif., 1921 and 1922. California State Printing Office, Sacramento, 1923.

Publications of the highway research board, division of engineering and industrial research, National Research Council:
Highway research projects in the United States, vol. 4, pt. 3, No. 21, October, 1922.
Apparatus used in highway research projects in the United States, vol. 6, pt. 4, No. 35, August, 1923.
Proceedings of the second annual meeting, vol. 6, pt. 1, No. 32, May, 1923.
Proceedings of the third annual meeting, vol. 8, pt. 1, No. 43, March, 1924.
Proceedings of the fourth annual meeting, May, 1925.

United States Department of Agriculture Bulletins:
The principles of the liming of soils, by Edmund C. Shorey. Farmers' Bul. 921. March, 1918.
Drainage methods and foundations for county roads, by E. W. James, Vernon M. Peirce, and Charles H. Moorefield. Dept. Bul. 724. December 21, 1918.
Capillary movement of soil moisture, by Walter W. McLaughlin. Dept. Bul. 835. 1920.
Absorption by colloidal and noncolloidal constituents, by M. S. Anderson and W. H. Fry. Dept. Bul. 1122. October 21, 1922.
Estimation of colloidal material in soils by absorption, by P. L. Gile and H. E. Middleton. Dept. Bul. 1193. February 15, 1924.
Tentative standard methods of sampling and testing highway materials. Dept. Bul. 1216. May, 1924.
The capillary distribution of moisture in soil columns of small cross section, by W. W. McLaughlin. Dept. Bul. 1221. April, 1924.
The chemical composition of soil colloids, by W. O. Robinson and R. S. Holmes. Dept. Bul. 1311. October, 1924.
The wilting coefficient for different plants and its indirect determination, by Lyman J. Briggs and H. L. Shantz. Bureau of Plant Industry Bul. 230. February, 1912.
The mechanics of soil moisture, by L. J. Briggs. Bureau of Soils Bul. 10. 1898.
The capillary movement of water in dry and moist soils, by L. J. Briggs and M. H. Lapham. Bureau of Soils Bul. 19. 1902.
The centrifugal method of mechanical soil analysis, by Lyman J. Briggs, D. O. Martin and J. R. Pearce. Bureau of Soils Bul. 24. 1904.
Studies on the movement of soil moisture, by Edgar Buckingham. Bureau of Soils Bul. 38. 1911.
The moisture equivalents of soils by Lyman J. Briggs and John W. McLane. Bureau of Soils Bul. 45. 1907.
Moisture content and physical condition of soils, by F. K. Cameron and F. E. Gallagher. Bureau of Soils Bul. 50. 1908.
The effect of soluble salts on the physical properties of soils, by R. O. E. Davis. Bureau of Soils Bul. 82. 1911.

United States Geological Survey Bulletin:
The colloid matter of clay and its measurement, by H. E. Ashley. Bul. 388. 1909.

Reprints from the Journal of Agricultural Research:
Effect of temperature on movement of water vapor and capillary moisture in soils, by G. J. Bouyoucos, vol. 5, No. 4, October 25, 1925.
Use of the moisture equivalent for the indirect determination of the hygroscopic coefficient, by F. J. Alway and J. C. Russel, vol. 6, No. 22, August 28, 1916.
Measurement of the inactive or unfree moisture in the soils by means of the dilatometer method, by Geo. J. Bouyoucos, vol. 8, No. 6, February 5, 1917.
Relation of the water retaining capacity of a soil to its hydroscopic coefficient, by F. J. Alway and G. R. McDole, vol. 9, No. 2, April 9, 1917.
Movement and distribution of moisture in the soil, by F. S. Harris and H. W. Turpin, vol. 10, No. 3, July 30, 1917.
Evaporation from the surfaces of water and river bed materials, by R. B. Sleight, vol. 10, No. 5, July 30, 1917.
Relation of movement of water in a soil to its hygroscopicity and initial moistness, by F. J. Alway and Guy R. McDole, vol. 10, No. 8, August 20, 1917.
A field study of the influence of organic matter upon the water-holding capacity of a silt-loam soil, by F. J. Alway and J. R. Neller, vol. 16, No. 10, March 10, 1919.
Effectiveness of mulches in preserving soil moisture, by F. S. Harris and H. H. Yao, vol. 23, No. 9. 1923.
The microscopic estimation of colloids in soil separates, by Wm. H. Fry, vol. 24, No. 10.
The movement of water in irrigated soils, by Carl S. Scofield, vol. 27, No. 9, March, 1924.

Journal of Agricultural Science:
The moisture equivalent of heavy clay soils, by A. F. Joseph and F. J. Martin, vol. 13, 1922.
The maximum water retaining capacity of colloidal soils. The interpretation of this and certain other soil moisture constants, by F. Hardy, vol. 13, 1923.
The physical significance of the shrinkage coefficient of clays and soils, by F. Hardy, vol. 13, 1923. p. 243.
Soil Science:
Moisture equivalent determinations of salt-treated soil, by L. T. Shark and D. D. Waynick, vol. 4, p. 464. 1917.
The movement of moisture in soils by capillarity, by W. Gardner, vol. 3, No. 4, 1919.
Capillary moisture holding capacity, by W. Gardner, vol. 3 No. 4, 1919.
The movement of moisture in soil by capillarity, by Willard Gardner, vol. 7, No. 4, pp. 314–315. 1919.
Capillary moisture-holding capacity, by Willard Gardner, vol. 7, No. 4, p. 319. 1919.
Relation of the moisture equivalent of soils to the moisture properties under field conditions of irrigation, by S. T. Harding, vol. 8, No. 4, 1919.
The moisture equivalent in relation to the mechanical analysis of soils, by H. E. Middleton, vol. 9, p. 159. 1920.
The effect of the initial moisture in a soil on moisture movement, by P. E. Karraker, vol. 10, p. 143. 1920.
The classification of soil moisture, by F. W. Parker, vol. 13, p. 43. 1922.
Proceedings of the American Society of Civil Engineers:
Progress report of the special committee to codify present practice on the bearing value of soils for foundations, vol. 47, No. 2, February, 1921.
Progress report of the special committee to codify present practice on the bearing value of soils for foundations, etc., vol. 51, No. 5, May, 1925.
Transactions of the American Society of Civil Engineers:
Highway research in Illinois, by Clifford Older, vol. 87, pp. 1181–1224. 1924.
Researches on the structural design of highways by the United States Bureau of Public Roads, by A. T. Goldbeck, vol. 88, p. 264. 1925.
Proceedings of the American Society for Testing Materials:
Physical properties of subgrade materials, by J. R. Boyd, vol. 22, pt. II. 1922.
Proceedings of the American Railway Engineering Association:
Report on unit pressures allowable on roadbeds of different materials, vol. 13, p. 388. 1912.
Transactions of the American Ceramic Society:
The colloid theory of plasticity, by Allerton S. Cushman, vol. 6, p. 65.
Reprint from the Journal of the American Chemical Society:
The effect of finely divided material on the freezing points of water, benzene and nitrobenzine, by F. W. Parker vol. 43, No. 5, May, 1921.
Proceedings of the National Academy of Sciences:
Pressure phenomena accompanying growth of crystals, by Stephen Taber, vol. 3, pp. 297–302.
Engineering News:
Life of physical railway property, vol. 70, No. 20. November 13, 1913. p. 972.
Texas soil requires paving base to be reinforced, vol. 75, No. 14, April 6, 1916.
Engineering News-Record:
Ice forming in clay soils will lift surface weights, by Stephen Taber, vol. 80, No. 6, February 7, 1918.
First frost is never responsible for cracked concrete roadways, by J. L. Harrison, vol. 80, No. 9, February 28, 1918.
Impervious bituminous wall suggested to prevent seepage under paving, by John W. Lowell, vol. 81, No. 5, August 1, 1918.
Variable designs for country highway systems, vol. 84, No. 5, February 20, 1920.
Engineering News-Record—Continued.
Value of topsoil as base for modern highways, by D. S. Humphrey, vol. 84, No. 12, March 18, 1920.
A detail of road foundations on clay, by John R. Rablin, vol. 88, No. 11, March 16, 1922.
North Carolina topsoil road theory and practice, vol. 89, No. 3, July 20, 1922.
Removal of capillary moisture in highway subgrades, by Charles H. Upham and H. F. Janda, vol. 93, No. 23. December 4, 1924.
Dirt roads improved by lime mixed with surface soil, by E. J. McCaustland, vol. 94, No. 26. June 25, 1925.
Engineering and Contracting:
Wells and permeability of soils, vol. 55, No. 13, March 30, 1921. p. 312.
Soil porosity and the distance between drainage channels, by L. Schmeer, vol. 41, No. 13. April 1, 1914. p. 398–9.
University of California Publications:
Variability in soils and its significance to past and future soil investigations, by Dean D. Waynick, vol. 3, No. 9, June 22, 1918.
Are soils mapped under a given type name by the Bureau of Soils method closely similar to one another, by Robert Larimore Pendleton, vol. 3, No. 12, June 30, 1919.
The moisture equivalent as influenced by the amount of soil used in its determination, by F. J. Veihmeyer, O. W. Isrealsen, and J. P. Conrad, Technical Paper No. 16, September, 1924.
University of Georgia Publication:
Research work on semigravel, topsoil and sand-clay and other road materials in Georgia, by C. M. Strahan. Bul. 59, vol. 22, June, 1922.
Iowa State College Publication:
The theory of underdrainage, by W. J. Schlick. Bul. 50, vol. 17, No. 17, September 25, 1918.
Michigan Agricultural College Publications:
Effect of temperature on some of the most important physical processes in soils, by George J. Bouyoucos. Technical Bulletin 22, July, 1915.
Calssification and measurement of the different forms of water in the soil by means of the dilatometer method, by Geo. J. Bouyoucos. Technical Bulletin 36, September, 1917.
The freezing point method as a new means of studying velocity of reaction between soils and chemical agents and behavior of equilibrium, by Geo. J. Bouyoucos and W. A. Landeman. Technical Bulletin 37, September, 1917.
Oregon Agricultural College Experiment Station Publication:
Irrigation and soil moisture investigations in Western Oregon, by W. L. Powers. Bul. 122, August, 1914.
Experiment Station Record:
Compact soil to increase its water content, by E. Gain. Vol. 8, p. 6. (Abstract from Precis de Cheinie Agricole. 1896. p. 57.)
Kentucky Agricultural Experiment Station:
Effect of initial moisture content on subsequent moisture movement in soil, by G. Roberts. Thirty-first annual report, pt. I, 1918.
Fourth Biennial Report of the California Highway Commission:
Subgrade treatment, November 1, 1924. p. 76.

CORRECTION

In the article on colors and forms of traffic signals proposed by the sectional committee of the American Engineering Standards Committee which appeared in the August issue of PUBLIC ROADS, under Rule 52 on page 136 the color temperature erroneously printed as 2.360° K should properly have been 2,360° K.

HIGHWAY RESEARCH BOARD ISSUES BULLETIN

THE Proceedings of the Fourth Annual Meeting of the Highway Research Board, recently issued, is a valuable contribution to scientific literature. It contains complete reports of the recent studies of the six active research committees of the board and is an extremely attractive bulletin.

The research committees of the board are organized as follows:

1. Committee on Economic Theory of Highway Improvement. *Chairman*, T. R. Agg, Iowa State College.
2. Committee on Structural Design of Roads. *Chairman*, A. T. Goldbeck, U. S. Bureau of Public Roads.
3. Committee on Character and Use of Road Materials. *Chairman*, H. S. Mattimore, Pennsylvania Highway Department.
4. Committee on Highway Traffic Analysis. *Chairman*, Geo. E. Hamlin, Connecticut Highway Commission.
5. Committee on Highway Finance. *Chairman*, H. R. Trumbower, U. S. Bureau of Public Roads.
6. Committee on Maintenance. *Chairman*, W. H. Root, Iowa Highway Commission.

The committees are composed of those men who have contributed to the scientific development of the highways and who are decidedly active in highway research.

The report of the Committee on the Economic Theory of Highway Improvement contains tables of the rolling plus air resistance for busses and automobiles with high-pressure cord tires and for trucks with pneumatic tires; data on the relation between the type of road and fuel consumption; highway transport costs; and the results of a study of tire wear. This report also contains a description of the studies now being carried on to determine the wind resistance of motor vehicles.

The report of the Committee on Structural Design of Roads contains reports on subgrade investigation; sand-clay road investigation; impact and static-load tests on road slabs; motor-truck impact tests; fatigue of concrete; theory of stresses in road slabs; stress measurement in road slabs; and skew-arch investigations. This report is well illustrated and contains much valuable information.

The Committee on Highway Finance report deals with several aspects of the financial questions so frequently encountered in a highway construction program. The report contains figures, charts, and tables that show such relations as total motor-vehicle revenues and total highway expenditures; gasoline tax rates in effect on July 1, 1924; highway expenditure and income; and other items that should be considered in the financial problem.

The report of the Committee on Highway Traffic Analysis contains interesting information on such topics as: (1) A study of the increase in motor vehicle registration to determine factors for forecasting future traffic; (2) the width of highway required to be constructed for the estimated life of the type of construction; (3) the economic value of eliminating bottle-neck points; and (4) highway transport surveys. A complete outline of highway transport surveys is given and should prove of value to all engineers interested in this subject as it indicates such items as the cost of the surveys, typical organizations and equipment required, and the kind of data to be taken.

The report of the Committee on Character and Use of Road Materials is extremely well illustrated and is indeed valuable information. The report contains studies of soundness tests for coarse aggregates; absorption of concrete in water as affected by the aggregates; effect of grading of the mineral aggregates in sheet asphalt and bituminous concrete construction relative to the deformation of the surfaces under traffic; and the recovering of bituminous material from aggregates without changing their character.

Surface treatment of gravel roads, crack fillers for concrete pavements, snow removal, road signs, and maintenance accounting form the body of the report of the Committee on Maintenance. This report contains the results of a recent study of bituminous crack fillers together with a complete analysis of the materials used.

The Highway Research Board is not of itself a research agency, but functions as a clearing house for all matters pertaining to highway research. Its functions are threefold: To prepare a comprehensive national program for highway research; to assist existing organizations to coordinate their activities; and to serve as a clearing house for information on completed and current research.

The board has recently enlarged its scope and at the present time is conducting fact-finding surveys on the economic value of reinforcement in concrete roads, the development of earth roads, and an investigation pertaining to culvert pipe.

At a recent meeting of the executive committee of the Highway Research Board, the date of the fifth annual meeting was set as December 3 and 4, 1925. This meeting will be held in the building of the National Academy of Sciences and the National Research Council, B and Twenty-first Streets, Washington, D. C. The program of the meeting will be announced through the technical press at an early date.

The Proceedings of the Fourth Annual Meeting of the board will be sent to highway engineers who make a written request to the Highway Research Board, National Research Council, B and Twenty-first Streets, Washington, D. C.

MOTOR VEHICLE REGISTRATIONS AND REVENUE, ETC.

FOR SIX MONTHS, ENDING JUNE 30, 1925

State	Individually and commercially owned: Grand total motor vehicles 6 months, 1925 [1]	Individually and commercially owned: Passenger cars [1]	Individually and commercially owned: Motor trucks [1]	Individually and commercially owned: Taxis, busses, and cars for hire	Official cars and trucks owned by State, etc. [1]	Motor cycles	Registration fees, licenses, permits, etc.: Total gross receipts	Registration fees, licenses, permits, etc.: Amount applicable to highway work by or under supervision of State highway department	Amount of registration fees paid for—: Passenger cars	Amount of registration fees paid for—: Motor trucks	Grand total motor vehicles first 6 months, 1924	Per cent increase of cars 1925 over 1924	State
Alabama	236,966	194,487	39,547	2,932		361	$1,882,557	$1,845,525			154,234	53.6	Alabama.
Arizona	59,809	51,667	8,142	(2)	858	286	372,855	372,855			50,409	18.6	Arizona.
Arkansas	148,981	127,803	19,131	2,047		185	2,991,180	2,641,180			116,700	27.6	Arkansas.
California	1,317,825	1,119,207	198,618	(2)	19,750	9,787	6,558,101	3,279,050	$3,746,835	$2,566,718	1,184,015	11.3	California.
Colorado	213,891	198,231	15,660	(2)		1,488	1,311,368	601,000	1,055,598	189,750	186,926	14.4	Colorado.
Connecticut	216,746	184,046	30,094	2,606	3,151	3,097	5,069,455	5,069,455	2,948,033	1,080,491	188,344	15.0	Connecticut.
Delaware	35,600	29,400	6,200	(2)		295	613,474	613,474	354,804	126,484	31,300	13.7	Delaware.
Florida	231,439	192,000	36,500	2,939		730	3,017,502	1,918,034			164,112	41.0	Florida.
Georgia	207,663	182,594	24,968	[3] 101		731	2,720,157	2,650,051	2,229,660	439,447	177,030	17.3	Georgia.
Idaho	[4] 73,500	[4] 65,000	[4] 8,500		970	450	[4] 1,426,100	[4] 356,525			62,175	18.2	Idaho.
Illinois	1,123,084	981,436	141,648	(2)		5,106	12,032,287	12,007,383	8,702,662	2,690,834	986,480	13.8	Illinois.
Indiana	523,783	452,192	68,685	[3] 2,906	308	3,639	4,279,463	4,139,170	3,058,220	939,881	581,899	(7)	Indiana.
Iowa	611,002	569,120	41,882	(2)	2,000	2,074	8,969,441	8,162,191			569,415	7.0	Iowa.
Kansas	406,990	366,271	40,719	(2)	1,884	1,046	4,476,890	4,297,814			360,796	12.8	Kansas.
Kentucky	233,828	208,305	25,523		1,147	546	3,585,157	3,541,157	2,724,616	774,338	203,028	15.1	Kentucky.
Louisiana	190,896	161,826	29,070			505	3,112,947	3,112,947			150,000	27.2	Louisiana.
Maine	[5] 126,200	[5] 104,750	[5] 18,295	[5] 3,155		[5] 1,200	1,905,724	1,905,724			110,282	14.4	Maine.
Maryland	208,338	194,766	10,600	2,972		3,719	2,065,033	1,652,027	1,426,601	250,447	178,153	16.9	Maryland.
Massachusetts	639,315	551,563	87,752	(2)		8,155	7,926,862	[5] 7,134,176	5,186,065	1,371,256	508,997	25.6	Massachusetts.
Michigan	798,460	716,233	82,227	(2)	3,233	2,540	11,763,067	5,763,067	8,407,037	2,481,847	764,423	4.4	Michigan.
Minnesota	519,168	479,629	39,189	350		2,622	9,037,663	9,037,663	7,867,097	913,553	462,777	12.1	Minnesota.
Mississippi	148,758	133,882	14,876			73	1,413,894		1,271,879	141,322	112,099	32.6	Mississippi.
Missouri	535,528	486,146	49,382	(2)	1,240	1,589	3,250,206	3,022,692			477,056	12.2	Missouri.
Montana	83,950	73,350	10,600	(2)	994	1,922	837,550		711,081	125,134	69,100	21.5	Montana.
Nebraska	295,341	264,780	30,561	(2)		868	3,625,172	2,718,879	2,951,971	587,325	273,236	8.1	Nebraska.
Nevada	17,939	15,070	2,869		350	76	188,891	188,891			15,961	12.4	Nevada.
New Hampshire	73,120	65,808	7,312		286	1,304	1,045,654	990,051			64,373	13.6	New Hampshire.
New Jersey	505,474	397,379	98,387	9,708		6,175	9,198,365	9,026,280	3,864,491	2,836,669	435,894	15.9	New Jersey.
New Mexico	42,205	40,550	1,267	388		184	445,628	261,557			34,951	20.7	New Mexico.
New York	1,404,653	1,136,978	237,233	30,442	10,624	15,737	23,057,565	17,293,174	14,057,217	6,450,795	1,233,362	13.8	New York.
North Carolina	[6] 315,000	[6] 282,750	[6] 30,000	[6] 2,250		[6] 1,000	[6] 4,983,700	[6] 4,490,000			[6] 285,546	10.3	North Carolina.
North Dakota	126,106	118,624	7,482			321	918,994	319,497	822,731	78,711	104,845	20.3	North Dakota.
Ohio	1,292,000	1,132,000	160,000		3,000	12,000	11,969,324	5,984,662			1,160,000	11.3	Ohio.
Oklahoma	420,000	390,000	30,000	(2)		800	4,112,723				308,906	35.9	Oklahoma.
Oregon	179,566	166,107	13,459	(2)	1,577	2,069	4,844,310	3,558,232	4,059,690	683,825	161,739	11.0	Oregon.
Pennsylvania	1,205,287	1,036,813	162,307	6,167	8,880	13,180	19,526,528	19,526,528	10,755,719	5,077,978	1,085,285	11.1	Pennsylvania.
Rhode Island	89,247	72,603	15,311	1,333	587	1,054	1,520,703	1,446,713	946,248	357,323	78,413	13.8	Rhode Island.
South Carolina	141,208	128,735	12,473	(2)	1,149	108	2,156,206	1,621,198	1,653,991	295,011	137,891	2.4	South Carolina.
South Dakota	150,335	138,257	11,680	398	712	280	2,279,479	1,006,904	2,039,291	234,768	126,813	18.5	South Dakota.
Tennessee	218,735	196,389	20,409	1,937		554	2,808,119	2,808,119			182,723	19.7	Tennessee.
Texas	848,661	773,464	72,505	2,692		2,201	12,081,524	8,676,292			661,919	28.2	Texas.
Utah	76,410	66,850	9,560			557	496,851	437,200			67,133	13.8	Utah.
Vermont	60,424	56,083	4,341			576	1,350,639	1,279,362	1,045,223	110,520	52,614	14.8	Vermont.
Virginia	225,800	222,500	3,300			1,500	3,813,317	3,617,650	3,100,951	484,711	225,343	.2	Virginia.
Washington	293,589	250,257	40,331	3,001	3,789	2,196	4,615,950	4,545,326	3,392,992	978,430	265,541	10.6	Washington.
West Virginia	184,200	158,400	22,450	3,350	1,135		2,898,418	2,898,418	2,030,637	493,638	154,772	19.0	West Virginia.
Wisconsin	534,662	476,188	58,474	(2)	437	2,864	7,800,438	7,420,000			473,913	12.8	Wisconsin.
Wyoming	42,600	38,000	4,600		200	200	437,000	437,000			38,200	11.4	Wyoming.
District of Columbia	82,427	71,158	10,631	638	1,939	1,324	105,278	105,278			72,954	13.0	District of Columbia.
Total	17,716,709	15,519,647	2,114,750	82,312	70,200	119,274	226,899,709	183,780,371	[8] 100,411,340	[8] 32,761,206	15,552,077	13.9	Total.

[1] Net number of cars and trucks registered shown when possible, excluding reregistrations, nonresident, and official exempt cars and trucks.
[2] Recorded with private cars or trucks.
[3] Motor busses only.
[4] Estimated from 3 months' return.
[5] Approximate.
[6] Estimate for registration year ending June 30.
[7] Decrease.
[8] Only data for 27 States shown

THE GASOLINE TAX IN THE FIRST SIX MONTHS OF 1925

State	Date of rate change 1925	Tax rate per gallon		Gross receipts Jan. 1 to June 30, 1925	Distribution of gross receipts			State
					Applied to road work			
		Jan. 1, 1925	June 30, 1925		Supervision State highway department	County and local road funds	Miscellaneous purposes	
		Cents	*Cents*					
Alabama		2	2	$963,520		$958,604	Collection costs, $4,916	Alabama.
Arizona		3	3	401,438	$200,719	200,719		Arizona.
Arkansas		4	4	1,520,789	1,170,789	350,000		Arkansas.
California		2	2	7,514,667	3,753,584	3,753,583	Collection costs, about $7,500	California.
Colorado		2	2	914,962	434,607	434,607	5 per cent administration, $45,748	Colorado.
Connecticut		1	1	527,671	527,671	0		Connecticut.
Delaware		2	2	157,291	157,291	0		Delaware.
Florida		3	3	2,731,387	1,431,843	715,921	Refunds and expenses, $583,623	Florida.
Georgia		3	3	1,837,203	612,401	612,401	State general fund, $612,401	Georgia.
Idaho		2	2	339,466	339,466	0		Idaho.
Illinois	No tax.	0	0					Illinois.
Indiana	4/1	2	3	[1] 3,214,588	2,246,438	962,876	Collection costs, $5,274	Indiana.
Iowa	4/16	0	2	978,855	326,285	652,570		Iowa.
Kansas	5/1	0	2	892,208	713,766	178,442		Kansas.
Kentucky		3	3	1,347,499	1,347,499	0		Kentucky.
Louisiana		2	2	1,091,691	1,091,691	0		Louisiana.
Maine		1	[2] 1	202,477	202,477	0		Maine.
Maryland		2	2	870,975	[3] 852,628	0	Refunds and collection costs, $18,347	Maryland.
Massachusetts	No tax.	0	0					Massachusetts.
Michigan	2/1	0	2	3,385,500	3,385,500	0		Michigan.
Minnesota	5/1	0	2	1,260,839	1,260,839	0		Minnesota.
Mississippi		3	3	1,079,701	523,495	523,495	Collection costs, $32,711	Mississippi.
Missouri	1/1	0	2	2,169,902	1,991,902	0	Collection costs and refunds, $178,000	Missouri.
Montana		2	2	226,229	36,229	117,542	State general fund, $72,458	Montana.
Nebraska	4/1	0	2	681,215	673,215	0	Collection costs, $8,000	Nebraska.
Nevada		2	[4] 2	100,228	50,114	50,114		Nevada.
New Hampshire		2	2	263,027	263,027	0		New Hampshire.
New Jersey	No tax.	0	0					New Jersey.
New Mexico	3/17	1	3	185,019	175,768	0	Collection costs, $9,251	New Mexico.
New York	No tax.	0	0					New York.
North Carolina	3/5	3	4	2,782,242	2,767,467	0	Collection costs, $14,775	North Carolina.
North Dakota		1	1	250,150	50,150	0	State general fund, $200,000	North Dakota.
Ohio	4/21	0	2	2,515,435	1,131,946	754,631	Municipal roads, $628,859	Ohio.
Oklahoma	3/23	2½	3	2,150,549	1,351,929	798,620		Oklahoma.
Oregon		3	3	1,336,593	1,275,664	0	Expense and refunds, $60,929	Oregon.
Pennsylvania		2	2	4,657,752	375,440	1,178,852	State general fund, $3,103,459	Pennsylvania.
Rhode Island	4/29	0	1	45,848	45,848	0		Rhode Island.
South Carolina	3/23	3	5	1,583,910	817,612	600,380	State general fund, $165,918 [5]	South Carolina.
South Dakota	3/10	2	3	772,937	772,937	0		South Dakota.
Tennessee	2/9	2	3	1,380,898	690,449	690,449		Tennessee.
Texas		1	1	2,113,572	1,585,179	0	Free school fund, $528,393	Texas.
Utah	4/1	2½	3½	429,363	428,000	0	Collection costs, about $1,363	Utah.
Vermont	2/26	1	2	171,867	171,867	0		Vermont.
Virginia		3	3	1,681,786	1,121,191	560,595		Virginia.
Washington		2	2	1,445,786	1,437,847	0	Collection costs, $7,939	Washington.
West Virginia		2	[6] 2	632,280	632,280	0		West Virginia.
Wisconsin	4/1	0	2	779,838	779,838	0		Wisconsin.
Wyoming	4/1	1	2½	130,190	129,560	0	Collection costs, $630	Wyoming.
District of Columbia		2	2	389,391	385,391	0	Refunds, $4,000	District of Columbia.
Total				60,108,734	39,719,839	14,094,401		Total.

[1] Refunds excluded.
[2] Changed to 3 cents on July 11, 1925.
[3] Baltimore received one-fifth of this amount, $170,526.
[4] Changed to 4 cents on July 1, 1925.
Part of disposal of first three months: New law excludes State genera lfund.
[6] Changed to 3½ cents on July 1, 1925.

UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

STATUS OF FEDERAL AID HIGHWAY CONSTRUCTION

AS OF

AUGUST 31, 1925

STATES	FISCAL YEARS 1917-1925			FISCAL YEAR 1926									BALANCE OF FEDERAL AID FUND AVAILABLE FOR NEW PROJECTS	STATES
	PROJECTS COMPLETED PRIOR TO JULY 1, 1925			PROJECTS COMPLETED SINCE JUNE 30, 1925			* PROJECTS UNDER CONSTRUCTION			PROJECTS APPROVED FOR CONSTRUCTION				
	TOTAL COST	FEDERAL AID	MILES	TOTAL COST	FEDERAL AID	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES		
Alabama	$ 5,970,097.71	$ 2,863,197.86	611.8	$ 573,244.10	$ 283,034.64	26.9	$ 14,838,392.56	$ 7,193,504.05	777.5	$ 300,107.34	$ 146,749.34	24.8	$ 2,322,170.11	Alabama
Arizona	9,580,133.43	5,016,119.94	613.6	237,926.90	145,397.06	7.1	2,043,979.33	1,270,492.41	157.2	276,880.71	180,420.97	35.6	1,948,910.62	Arizona
Arkansas	13,310,190.06	5,380,181.73	1,048.9	127,585.44	61,163.46	8.3	7,415,243.72	3,357,050.45	390.6	1,622,859.12	778,529.39	131.8	760,971.97	Arkansas
California	22,346,175.99	10,719,249.61	894.8	1,026,130.46	509,752.08	24.4	10,182,004.31	4,983,478.43	261.1	1,686,658.50	761,081.95	89.3	2,614,546.93	California
Colorado	11,876,703.94	6,067,894.34	651.2	352,483.31	182,668.63	16.5	4,231,281.75	2,115,125.88	203.6	696,482.73	354,874.34	34.3	2,224,944.81	Colorado
Connecticut	4,558,839.29	1,819,368.66	101.6	575,452.78	171,947.14	9.5	1,909,405.24	609,235.48	29.8				1,259,701.72	Connecticut
Delaware	4,261,559.81	1,496,190.65	107.1	383,163.86	180,583.86	12.1	76,668.90	31,961.10	0.2	990,042.66	388,784.75	22.7	10,912.65	Delaware
Florida	2,959,273.72	1,405,487.97	96.3				8,787,223.95	4,279,162.51	261.8	776,663.27	295,728.86	11.8	1,207,389.66	Florida
Georgia	20,156,002.37	9,408,366.46	1,478.3	962,445.36	423,355.93	50.9	10,828,976.67	5,350,287.49	706.6	1,191,944.78	565,915.77	81.0	704,838.35	Georgia
Idaho	9,394,676.80	4,815,332.26	600.1	52,764.61	29,828.56	14.9	2,537,676.75	1,600,882.02	142.5	786,334.43	470,008.62	69.2	706,986.54	Idaho
Illinois	40,010,481.10	18,640,076.28	1,236.2	639,665.66	267,490.93	19.8	8,449,891.73	4,091,834.64	284.6				3,657,180.15	Illinois
Indiana	13,639,172.65	6,562,455.68	422.1	1,071,523.96	516,206.70	33.6	15,564,525.88	7,306,154.67	439.0	848,584.16	419,630.56	23.2	1,465,017.37	Indiana
Iowa	27,272,285.21	11,107,492.99	1,996.9	102,290.50	39,495.95	16.3	8,049,447.05	3,575,941.22	461.5	731,202.22	364,295.00	109.9	2,337,868.84	Iowa
Kansas	26,399,695.77	9,755,273.32	831.4	1,920,935.60	783,687.96	75.0	11,491,869.89	4,952,358.43	563.9	797,516.67	326,967.24	42.9	1,573,958.05	Kansas
Kentucky	14,832,324.26	6,205,994.59	594.9	553,446.24	219,076.66	17.8	7,882,919.22	3,522,706.27	281.0	590,422.33	295,211.16	40.0	1,553,010.73	Kentucky
Louisiana	11,939,424.97	5,279,870.86	927.6	875,723.59	411,312.04	64.9	2,772,603.62	1,325,240.49	108.8	356,130.73	178,065.36	2.8	1,077,155.26	Louisiana
Maine	8,174,281.31	3,907,870.33	281.4	173,275.15	85,733.59	6.6	1,311,335.31	551,480.38	42.2				1,236,169.70	Maine
Maryland	9,132,506.90	3,849,383.15	294.4				2,070,480.66	884,007.47	65.7	1,139,721.78	546,339.26	75.3	10,703.12	Maryland
Massachusetts	14,047,656.22	5,467,661.28	300.6	303,451.64	89,080.00	4.4	5,416,418.53	1,414,104.74	83.3	892,826.32	318,076.37	12.2	1,730,748.61	Massachusetts
Michigan	16,234,000.80	7,329,316.91	612.6	1,957,578.61	929,997.15	88.8	13,133,369.02	6,127,491.90	394.5	1,004,764.44	389,378.76	0.6	3,349,762.38	Michigan
Minnesota	30,415,685.89	12,738,642.04	2,721.2				9,146,490.80	4,021,900.00	781.0	1,021,808.56	208,800.00	72.0	492,269.96	Minnesota
Mississippi	10,292,285.79	4,989,702.73	803.4	952,131.44	475,374.67	67.6	8,104,412.27	4,047,450.48	439.0	1,074,297.43	537,118.68	68.6	786,168.44	Mississippi
Missouri	17,368,156.67	8,219,411.43	1,118.9	1,448,054.02	695,165.95	55.7	26,255,129.47	10,815,100.30	819.1	1,425,163.43	160,507.15	37.5	489,404.17	Missouri
Montana	10,156,600.41	5,317,523.15	921.6	449,444.40	390,460.39	49.5	1,703,364.88	1,187,274.00	134.1	971,621.92	542,524.18	116.6	4,435,443.28	Montana
Nebraska	9,306,374.36	4,389,523.50	1,570.6	795,963.75	396,021.48	66.8	7,638,135.16	3,800,068.85	782.5	2,943,547.56	1,456,650.78	297.4	3,004,832.39	Nebraska
Nevada	4,917,465.69	3,088,299.78	357.3	176,699.88	131,175.94	16.2	5,120,750.89	4,289,231.40	431.6	125,098.64	109,736.51	22.5	228,453.37	Nevada
New Hampshire	4,165,697.96	1,986,226.67	208.1				1,191,106.61	561,362.43	37.9	50,919.49	22,558.87	2.1	233,718.83	New Hampshire
New Jersey	11,961,357.45	3,820,679.99	219.1	568,121.43	131,911.06	8.1	9,554,745.73	3,324,061.87	67.8	658,080.63	205,446.25	15.7	50,612.83	New Jersey
New Mexico	8,717,999.18	4,914,070.61	1,081.3	1,473,170.37	987,112.81	134.7	2,847,896.13	1,835,025.39	259.9	406,214.35	253,070.82	29.6	1,796,842.37	New Mexico
New York	28,597,769.67	12,229,076.53	831.5	2,702,132.52	1,051,190.12	66.8	29,396,225.75	9,698,510.10	596.0	10,127,400.00	2,679,401.45	177.8	4,739,850.80	New York
North Carolina	21,014,460.41	8,746,464.59	1,119.8	1,114,845.28	437,085.30	34.4	7,793,610.79	3,363,112.05	191.5	2,055,720.25	884,513.17	58.5	577,486.89	North Carolina
North Dakota	10,829,263.62	5,268,930.47	1,917.5	310,319.25	155,029.12	92.5	3,616,874.00	1,824,088.87	465.4	946,269.54	473,134.67	113.8	1,833,755.87	North Dakota
Ohio	41,572,252.81	15,244,993.93	1,191.1	1,187,261.09	392,270.66	34.1	10,288,633.77	3,778,391.31	308.6	4,164,866.39	1,564,718.51	113.4	1,974,384.59	Ohio
Oklahoma	20,787,084.94	9,672,890.34	852.2	1,529,982.01	684,504.73	52.3	5,501,764.53	2,626,747.20	259.3	1,766,875.55	849,421.20	95.2	473,978.53	Oklahoma
Oregon	14,388,188.70	7,142,364.63	794.6	216,169.60	124,212.68	10.2	2,829,653.13	1,630,589.68	127.2	1,120,927.02	505,715.55	92.1	293,519.46	Oregon
Pennsylvania	43,054,835.19	16,222,023.97	850.3	661,585.18	191,522.50	11.8	32,501,906.46	8,640,032.64	564.2	6,849,582.03	2,001,018.33	152.1	937,263.56	Pennsylvania
Rhode Island	2,628,496.20	1,119,688.09	64.8				2,460,499.34	654,039.59	35.3	82,769.50	27,900.00	1.9	500,316.32	Rhode Island
South Carolina	11,163,347.84	5,121,267.54	1,235.9	969,030.47	315,193.36	49.2	5,649,786.65	2,668,789.19	325.0	1,002,147.52	412,092.84	41.0	232,188.07	South Carolina
South Dakota	12,091,434.67	5,989,879.00	1,447.9	861,885.50	412,489.09	92.6	7,137,671.31	8,405,497.96	1,007.9	184,120.15	92,080.06	27.5	44,665.89	South Dakota
Tennessee	13,789,140.98	6,732,079.77	497.9	2,163,355.52	1,065,751.53	70.4	9,930,886.09	4,436,772.39	352.4	128,336.55	64,168.27	10.8	1,363,400.04	Tennessee
Texas	54,120,970.63	21,057,940.12	3,907.1	1,805,447.98	761,222.85	153.8	23,591,944.63	9,921,184.80	1,362.1	3,904,117.08	1,620,469.66	296.8	2,818,696.87	Texas
Utah	6,259,169.41	3,819,625.91	423.1	132,178.99	99,890.36	5.9	2,876,056.20	1,937,053.10	220.0	350,634.01	257,973.13	35.4	856,784.51	Utah
Vermont	3,015,174.51	1,462,894.45	107.8	22,599.35	11,299.67	0.2	1,196,915.15	572,446.74	26.4	586,102.70	205,752.15	12.9	660,488.99	Vermont
Virginia	13,099,720.01	6,271,998.20	676.2	1,720,105.73	850,257.20	80.8	8,491,566.90	3,725,275.21	271.9	2,161,254.07	979,362.48	76.1	228,768.91	Virginia
Washington	13,352,504.18	6,117,211.67	526.7	1,049,945.31	437,338.64	25.0	2,094,224.66	988,900.00	102.3	1,130,579.45	509,000.00	35.3	963,245.49	Washington
West Virginia	7,343,200.86	3,230,293.33	326.7	252,664.30	123,013.89	12.8	4,944,376.90	2,063,264.68	136.0	3,163,926.54	1,144,830.33	89.3	7,152.77	West Virginia
Wisconsin	21,807,140.91	8,919,640.62	1,451.7				4,734,981.91	2,328,946.59	217.6	1,236,349.35	607,256.50	82.8	3,712,709.29	Wisconsin
Wyoming	6,809,919.33	4,739,096.67	982.0	473,184.83	278,096.58	42.1	3,758,189.67	2,366,555.53	256.9	99,681.78	63,996.00	12.1	182,936.22	Wyoming
Hawaii							342,277.22	97,440.00	6.5				637,088.00	Hawaii
TOTALS	740,140,790.82	325,654,346.00	41,898.3	34,714,362.86	15,927,392.60	1,733.2	379,693,773.29	165,141,632.98	16,229.8	64,406,373.89	25,218,264.25	2,974.2	66,308,374.27	TOTALS

* Includes projects reported completed (final vouchers not yet paid) totaling: Estimated cost $ 101,031,316.39 Federal aid $ 44,794,856.73 Miles 4,390.6